INDUSTRIAL HYGIENE AND TOXICOLOGY

VOLUME I

INDUSTRIAL HYGIENE AND TOXICOLOGY

In Two Volumes

VOLUME I

INDUSTRIAL HYGIENE AND TOXICOLOGY

2 terms

FRANK A. PATTY, *Editor*

Contributors:

J. BROZEK
L. F. CURTISS
E. E. DART
W. B. DEICHMANN
D. O. HAMBLIN
I. HARTMANN
F. F. HEYROTH
F. R. HOLDEN
G. W. JONES
R. A. KEHOE
J. B. LITTLEFIELD
C. P. MC CORD
F. A. PATTY
L. SCHWARTZ
H. SPECHT
J. H. STERNER
J. F. TREON
W. N. WITHERIDGE

VOLUME I

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PREFACE

Industrial hygiene has been recognized and practiced from the time of Pliny down through the ages. It is the present concept of industrial hygiene that is relatively new—the concept of anticipating and recognizing potentially harmful situations and applying engineering control measures before serious injury results. There are some who question industry's ability to control all harmful exposures; and there is quite naturally a tendency to take the easy way out of a difficulty by substituting materials of low or moderate toxicity for those of a hazardous nature. Nevertheless, where incentives such as low cost, availability, or superior properties of a hazardous material justify the provision of positive engineering controls, they can be supplied promptly.

It is said that artisans are born rather than made, but there can be no doubt that industrial hygienists must be made, and it takes years to mellow some of us with sufficient understanding so that we can use our knowledge of the basic principles of industrial hygienc to the best advantage in accomplishing our goal.

Depending somewhat upon where we acquire our academic training and initial experience in field work, we are likely to start out with the concept that industry has one purpose—to make money—and that, in following that urge, the humanitarian aspects are apt to be neglected. So it is with somewhat of a shock that some of us learn that many industries are eagerly taking the initiative in improving the working environment of their employees. Our first ideas of introducing hygiene to industry are likely to involve some means of maneuvering into a position in which our recommendations for control measures are to be accepted as commandments not to be questioned and not, upon penalty of closing up shop, to be ignored. It is only gradually that we become aware of the fact that in promoting anything to the American public a sound idea "takes" more quickly and develops faster if it is "sold" rather than presented as an ultimatum. As a people we basically resent being told bluntly that we have to do a thing: we much prefer to "discover" for ourselves that the proposed new course is correct and therefore to our advantage. Adams* expresses these ideas well in his recent book, from which I quote:

> "The American is a composite of almost all races, nationalities, and classes . . . He hates a bit and bridle as heartily as does a young colt . . . There *are* dirty politicians, dirty labor leaders, dirty business men—black markets, some selfish and dirty consumers—but the Americans, now 138,000,000 of them, *the American people*, are the hope of the world and of the whole future of humanity."

The industrial hygienist becomes aware that salesmanship is a necessary part of his practice. The salesman will think of the "buyer's" point of view and, first of

* J. T. Adams, *Big Business in Democracy*. Scribner's, New York, 1946.

all, develop his recommendations for environmental controls with the understanding of an economist, and then stress all the advantages. He will simplify his work by taking advantage of the views of production engineers and occasionally going them one better by saving them money in the conservation of materials or in the recovery of a by-product. One cardinal rule he learns early is not to "bluff" or try to impress his audience with his superior knowledge. Some few persons have the ability to "get away with it," but the odds are against them and it is much safer to work on the same plane as our audience whether that means a step down or a jump up, and it helps to imagine one's self in the position of the man one is trying to influence.

Industrial hygiene may be defined as *the science and art of preserving health through the recognition, evaluation, and control of environmental causes and sources of illness in industry*. It resolves itself into the problem of finding factors or conditions in workplaces that may cause or contribute to the illness or serious discomfort of employees, and of devising methods and means of eliminating or controlling such conditions.

It would be a mistake to attempt to give the impression that industrial hygiene is pure science, or that it is restricted to the art of applying scientific principles: much of it involves a liberal use of common sense or what is perhaps better known as "horse sense." The job will never become monotonous or routine because the chemist, the engineer, and the physicist will keep introducing new and more or less hazardous materials and processes that require new developments for the evaluation and control of exposures attendant to their use. Neither is the job glamorous or spectacular, and much of it is hard work bordering on drudgery, but it has its compensations.

> I should like to narrate an incident that, because of its fundamentality and at the same time dramatic departure from the daily routine of an industrial hygienist, may be worth describing without retouching. One of the pioneers in industrial medicine and hygiene whom most readers will recognize without further identification might have regarded this incident as an "acorn.*" However, since no tangible reward or token of appreciation was either anticipated or received and the only special remuneration was the feeling of satisfaction that goes with accomplishing any job, assumed or assigned, it was considered all in the day's work.
>
> While busily engaged at my office one morning in the industrial hygienist's favorite occupation of pouring over survey reports, I received a telephone call: "This is Dr. ———, chemist over at ——— Dry Dock. Here's something I think you should know about and maybe you will want to come over and look around. We just sent a man to the hospital and we have two more who are laid up and in a serious condition. The ——— was docked here just two weeks ago for repairs and conversion and out of the 2,000 men working on her, over 100 are affected with some sort of breaking out and itch and all the men are threatening to quit if we don't find out what's wrong and correct it. The boat's been in the tropics for some time and the workmen fear some tropical disease is responsible for this outbreak."
>
> Yes, I did want to look around, and within an hour was aboard the ship and observed many of the afflicted men at work. There was considerable grumbling and an abundance of dirty looks. Several men wore bandages over vesicular patches and on a few there was evidence of a generalized fine vesiculation. We went through the ship from stem to stern and forecastle to bilge. It was like a beehive: men were cutting with torches, sawing out panels,

* C. P. McCord, *A Blind Hog's Acorns*. Cloud, Inc., Chicago, 1945.

knocking off plaster, shoveling out debris and filth, scrubbing, and removing the interior furnishings preparatory to refitting the boat completely. Admittedly the ship was dirty—in fact, in some areas it was filthy—but so what! Next we went to the first-aid room to see the attendant and find out what, if any, information could be obtained there. The place was crowded with patients, and while we waited to see the attendant first-aid man we could hear the grumblings of the waiting patients, who complained of "filthy working conditions" and that, if the health department were not called in to condemn the place, everyone should quit before they became ill—that the place was "infested with fleas" and that they didn't "want any tropical fevers." Finally the harassed attendant came to us, but he had little to offer except to comment that the cases and complaints were getting more numerous and that he certainly hoped we could do something.

We had seen the situation: a once luxuriant ship, somewhat filthy in spots, an explosive outbreak of dermatitis in nearly ten per cent of the 2,000 men at work on the ship, no reported cases among the many thousands of workmen in adjacent areas of the same shipyard, and, unless something were done quickly, work on this desperately needed troop ship and possibly in the entire yard would stop.

The job looked interesting if not easy. We collected samples of everything we could get loose—plaster, upholstery, hair stuffing, sweepings, scrapings from panels and floors, and samples of the different woods and sawdusts, and returned to the laboratory. The samples were turned over to the chemists and microscopists to look for fumigants, insecticides, alkalies, and other common irritants, as well as any signs of insects or parasites. Two members of the staff were inveigled into joining me in making patch tests with some of the materials after saturating them with alcohol as a precautionary measure. While these tests were in progress a medical associate told me with an air of finality that our company had called in, as consultant, an authority on dermatology and that he planned to leave the matter entirely in the consultant's hands. When I took the story to my immediate superior he said it was very interesting, and sometime when he had more time I should "tell him all about it." I telephoned the consultant dermatologist and inquired if he had seen the cases and had any ideas of what might cause the difficulty. Yes, he had seen them, and, except for the fact that it didn't make sense, he would say that they resembled poison-ivy cases. That agreed with what we had seen on the job, but we had not seen any poison ivy! After all of the chemical and microscopic tests proved negative except for an insignificant amount of arsenic in the sweepings, there remained only the possibility that the patch tests might indicate an irritant. After 48 hours, and with all patch tests negative, the shipyard's chemist reported that there were several more cases, including an electrician working on the dock beside the boat, and that a walkout seemed imminent even though the ship was desperately needed for a troop transport.

The fact that an electrician who possibly had not been on the boat was affected gave an indication that the problem might be attacked from epidemiological approach by personally interviewing some of the afflicted men. Discussion of personal matters with employees, especially shipyard workers, is ordinarily something to be avoided, but in this instance approval of such interviews was readily obtained from all parties concerned. Aided by the chemist and two safety engineers, we went out on the job and talked to some of the affected men, including the electrician, who had never been on the suspected ship, and a security policeman, who was seriously affected and had been aboard the ship only once for a few minutes. This introduced a strong element of doubt about the ship's being the contact source and diverted our attention to other possible sources of irritant material. It developed that nearly all cases were on the day shift. The electrician's case had been diagnosed "cable rash," but, since the characteristics of his lesions were similar to those of the other workmen, we did not waste time examining the cables with which he had been working. Instead, we investigated all the possible exposure sources where the men spent their time when they were off the ship: where

they ate their lunch, where they loafed, and the route they took to and from work. We found what appeared to be some damaged oil drums in a pile on a sand lot where several men had spent their lunch hour within the shipyard grounds, but about a block away from the dock to which the boat was tied. The drums were punctured or otherwise damaged and, for the most part, were empty, but three or four contained some dark oily liquid. Close examination of these drums revealed lettering still visible on one which read *Cashew Shell Liquid'*

The cause of the epidemic had been found.

At the shipyard, management quickly announced the facts over a public address system to the workmen so that their fears would be allayed. A strike was averted, and the ship was completed ahead of schedule. Further investigation revealed that cashew shell liquid had been spilled on the dock to some extent, in the street to a considerable amount, and extensively scattered over the sand lot in question. Many of the men working at refinishing and repairing this ship had sat on the sand, or the drums themselves, during the noon hour while they ate their lunches. Others had stretched out in the sun, bare-backed, on the contaminated sand. A check into the source of the drums revealed that a cargo of 1000 drums of the liquid had arrived and been unloaded on the opposite side of this same dock about one month previously. This work had been done by an outside contractor who had dumped the damaged drums onto the unused lot.

At our suggestion, all suspicious-looking spots were covered with chlorinated lime, the dock was cleaned and scrubbed, the drums disposed of, and dirt filled in on the sand lot. The dermatitis, which by now was starting to appear in the homes of workmen, from contact with soiled clothing, quickly disappeared. My colleague, the shipyard's chemist, however, in a sincere effort to convince himself and others of the potency of the cashew liquid, became impatient at negative results obtained in 24 hours with one tiny patch test and tried four more generous patches with samples from different drums. A few days later he joined those who had been hospitalized.

This is not a medical book nor is it intended for legal reference. Its primary purpose is not to aid in the diagnosis and treatment of disease, the winning of compensation, or the refutation of false claims. If it should prove of use in such instances by making some facts more widely available, it may be presumed that the more light that can be thrown upon these phases of industrial medicine and industrial relations the better. It is hoped that much information of use in preventive medicine is included. Diagnostic signs of absorption or of early effects, in advance of injury, are eagerly sought by the progressive industrial physician, and, although time-proved and recognized tests are disappointingly few, the research-minded industrial physician will find opportunities for increasing this field of knowledge. The object of this book is to present industrial hygiene and toxicology in simple, understandable terms in sufficient detail to be of some use to all persons interested in safeguarding the health and welfare of working people and in improving the working environment. Essential requisites for the completely successful advancement of the health and safety of the breadwinning population include: (*1*) competent persons in health and safety maintenance departments; (*2*) managerial interest and appreciation of the benefits to be derived from health and safety work; and (*3*) teamwork—camaraderie, and cooperative efforts among industrial hygiene, medical, and safety personnel.

The welfare of an individual workman involves not only a working environment that gives reasonable assurance of freedom from accidental injury or occupational

disease, but also his mental, temperamental, and physical fitness for the work to be done. Incentive, whether in the form of tangible assets to supply the necessities and some of the pleasures of life, or some expression of interest or recognition of accomplishments, ability, and efforts may be involved indirectly, but are somewhat outside the field of industrial hygiene.

It is not possible to maintain a uniform style in a collaboration, but the collective viewpoints compensate for some variations in style. In Chapter Thirty-Five considerable variation will be noted in the length of discussions. Much of this follows a premeditated plan to give full discussion where most needed and to avoid duplication. Some, however, reflects the degree of personal familiarity of the authors of this part of the book with the occupation under discussion. Where information is desired on an industry not listed, significant processes of the industry may be found elsewhere. Many cross references of this nature have been included. The book is liberally supplied with references for the benefit of those who wish to pursue the subjects in greater detail.

Acknowledgments

The contributors are to be congratulated for their doggedness in sticking to the task through many adversities, and, in some instances, inordinate demands upon their time. To the early contributors, may I express my appreciation of your indulgence during many discouraging delays. I should like also to express appreciation to Mrs. Ruth B. Patty for valuable assistance in editing, checking, and reading proof; to Mrs. Kathleen Kumler for reading proof and assistance in preparing the index. Credit should be extended to Lucille Rokicki and Suzanne Wickett, who have done much of the secretarial work. The courtesy of various individuals, companies, societies, and publishing houses in permitting reproduction of some of the tables and illustrations is gratefully acknowledged.

FRANK A. PATTY

Detroit, Michigan
October, 1948

LIST OF CONTRIBUTORS
to Volume I

Josef Brozek, Ph.D., Assistant Professor, Laboratory of Physiological Hygiene, University of Minnesota, School of Public Heath, Minneapolis, Minnesota — Chapter 4: *Personal Factors in Competence and Fatigue.*

Leon F. Curtiss, Ph.D., Radioactivity Section, United States Bureau of Standards, Washington, D. C. — Chapter 9: *Radiant Energy and Radium.*

Edward E. Dart, M.D., Medical Director, Pacific Industrial Hygiene Laboratories, 354 Hobart Street, Oakland, California — Chapter 15: *Dust and Its Role in the Causation of Occupational Disease.*

Irving Hartmann, M.A., M.E., Ph.D., Supervising Physicist, Experimental Coal Mine and Dust Explosions Research Section, Explosives Branch, Central Experiment Station, United States Bureau of Mines, Pittsburgh, Pennsylvania — Chapter 13, Section 2: *Explosion and Fire Hazards of Combustible Dusts.*

George W. Jones, Supervising Chemist, Gaseous Explosions Section, Explosives Branch, Central Experiment Station, United States Bureau of Mines, Pittsburgh, Pennsylvania — Chapter 13, Section 1: *Fire and Explosion Hazards of Combustible Gases and Vapors.*

John B. Littlefield, Assistant Technical Director, Chemical Department, American Brake Shoe Company, Mahwah, New Jersey — Chapter 2: *Industrial Hygiene Records and Reports.*

Carey P. McCord, M.D., Medical Director, The Industrial Health Conservancy Laboratories, Detroit, Michigan — Chapter 12: *The Visible Marks of Occupation and Occupational Diseases.*

Frank A. Patty, Director, Industrial Hygiene Service, General Motors Corporation, Detroit Michigan — Chapter 1: *Industrial Hygiene—Retrospect and Prospect.* Chapter 3: *The Industrial Hygiene Survey and Personnel.* Chapter 7: *The Mode of Entry and Action of Toxic Materials.* Chapter 8: *Sampling and Analysis of Atmospheric Contaminants.* Chapter 14: *Respirators and Respiratory Protective Devices.*

Louis Schwartz, M.D., Medical Director (Retired), *formerly* Chief, Dermatology Section, Division of Industrial Hygiene, United States Public Health Service, Washington, D. C. — Chapter 11: *Occupational Dermatoses.*

Heinz Specht, Physiologist, Laboratory of Physical Biology, National Institute of Health, Bethesda, Maryland — Chapter 6: *Physiological Effects of Abnormal Atmospheric Pressure.*

William N. Witheridge, Ventilation Consultant, Industrial Hygiene Service, General Motors Corporation, Detroit, Michigan — Chapter 5: *Environmental Factors in Fatigue and Competence.* Chapter 10: *Ventilation.*

ATOMIC WEIGHTS, 1948

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Element	Symbol	Atomic number	Atomic weight	Element	Symbol	Atomic number	Atomic weight
Aluminum	Al	13	26.97	Molybdenum	Mo	42	95.95
Antimony	Sb	51	121.76	Neodymium	Nd	60	144.27
Argon	A	18	39.944	Neon	Ne	10	20.183
Arsenic	As	33	74.91	Nickel	Ni	28	58.69
Barium	Ba	56	137.36	Nitrogen	N	7	14.008
Beryllium	Be	4	9.02	Osmium	Os	76	190.2
Bismuth	Bi	83	209.00	Oxygen	O	8	16.0000
Boron	B	5	10.82	Palladium	Pd	46	106.7
Bromine	Br	35	79.916	Phosphorus	P	15	30.98
Cadmium	Cd	48	112.41	Platinum	Pt	78	195.23
Calcium	Ca	20	40.08	Potassium	K	19	39.096
Carbon	C	6	12.010	Praseodymium	Pr	59	140.92
Cerium	Ce	58	140.13	Protoactinium	Pa	91	231
Cesium	Cs	55	132.91	Radium	Ra	88	226.05
Chlorine	Cl	17	35.457	Radon	Rn	86	222
Chromium	Cr	24	52.01	Rhenium	Re	75	186.31
Cobalt	Co	27	58.94	Rhodium	Rh	45	102.91
Columbium	Cb	41	92.91	Rubidium	Rb	37	85.48
Copper	Cu	29	63.54	Ruthenium	Ru	44	101.7
Dysprosium	Dy	66	162.46	Samarium	Sm	62	150.43
Erbium	Er	68	167.2	Scandium	Sc	21	45.10
Europium	Eu	63	152.0	Selenium	Se	34	78.96
Fluorine	F	9	19.00	Silicon	Si	14	28.06
Gadolinium	Gd	64	156.9	Silver	Ag	47	107.880
Gallium	Ga	31	69.72	Sodium	Na	11	22.997
Germanium	Ge	32	72.60	Strontium	Sr	38	87.63
Gold	Au	79	197.2	Sulfur	S	16	32.066
Hafnium	Hf	72	178.6	Tantalum	Ta	73	180.88
Helium	He	2	4.003	Tellurium	Te	52	127.61
Holmium	Ho	67	164.94	Terbium	Tb	65	159.2
Hydrogen	H	1	1.0080	Thallium	Tl	81	204.39
Indium	In	49	114.76	Thorium	Th	90	232.12
Iodine	I	53	126.92	Thulium	Tm	69	169.4
Iridium	Ir	77	193.1	Tin	Sn	50	118.70
Iron	Fe	26	55.85	Titanium	Ti	22	47.90
Krypton	Kr	36	83.7	Tungsten	W	74	183.92
Lanthanum	La	57	138.92	Uranium	U	92	238.07
Lead	Pb	82	207.21	Vanadium	V	23	50.95
Lithium	Li	3	6.940	Xenon	Xe	54	131.3
Lutecium	Lu	71	174.99	Ytterbium	Yb	70	173.04
Magnesium	Mg	12	24.32	Yttrium	Y	39	88.92
Manganese	Mn	25	54.93	Zinc	Zn	30	65.38
Mercury	Hg	80	200.61	Zirconium	Zr	40	91.22

CONVERSION TABLE FOR GASES AND VAPORS[a]

(Milligrams per Liter to Parts per Million and Vice Versa; 25° C. and 760 mm. Mercury Barometric Pressure)

Molecular Weight	1 mg./l. p.p.m.	1 p.p.m. mg./l.	Molecular Weight	1 mg./l. p.p.m.	1 p.p.m. mg./l.	Molecular Weight	1 mg./l. p.p.m.	1 p.p.m. mg./l.
1	24,450	0.0000409	51	479	0.002086	101	242.1	0.00413
2	12,230	.0000818	52	470	.002127	102	239.7	.00417
3	8,150	.0001227	53	461	.002168	103	237.4	.00421
4	6,113	.0001636	54	453	.002209	104	235.1	.00425
5	4,890	.0002045	55	445	.002250	105	232.9	.00429
6	4,075	.0002454	56	437	.002290	106	230.7	.00434
7	3,493	.0002863	57	429	.002331	107	228.5	.00438
8	3,056	.000327	58	422	.002372	108	226.4	.00442
9	2,717	.000368	59	414	.002413	109	224.3	.00446
10	2,445	.000409	60	408	.002554	110	222.3	.00450
11	2,223	.000450	61	401	.002495	111	220.3	.00454
12	2,038	.000491	62	394	.00254	112	218.3	.00458
13	1,881	.000532	63	388	.00258	113	216.4	.00462
14	1,746	.000573	64	382	.00262	114	214.5	.00466
15	1,630	.000614	65	376	.00266	115	212.6	.00470
16	1,528	.000654	66	370	.00270	116	210.8	.00474
17	1,438	.000695	67	365	.00274	117	209.0	.00479
18	1,358	.000736	68	360	.00278	118	207.2	.00483
19	1.287	.000777	69	354	.00282	119	205.5	.00487
20	1,223	.000818	70	349	.00286	120	203.8	.00491
21	1,164	.000859	71	344	.00290	121	202.1	.00495
22	1,111	.000900	72	340	.00294	122	200.4	.00499
23	1,063	.000941	73	335	.00299	123	198.8	.00503
24	1,019	.000982	74	330	.00303	124	197.2	.00507
25	978	.001022	75	326	.00307	125	195.6	.00511
26	940	.001063	76	322	.00311	126	194.0	.00515
27	906	.001104	77	318	.00315	127	192.5	.00519
28	873	.001145	78	313	.00319	128	191.0	.00524
29	843	.001186	79	309	.00323	129	189.5	.00528
30	815	.001227	80	306	.00327	130	188.1	.00532
31	789	.001268	81	302	.00331	131	186.6	.00536
32	764	.001309	82	298	.00335	132	185.2	.00540
33	741	.001350	83	295	.00339	133	183.8	.00544
34	719	.001391	84	291	.00344	134	182.5	.00548
35	699	.001432	85	288	.00348	135	181.1	.00552
36	679	.001472	86	284	.00352	136	179.8	.00556
37	661	.001513	87	281	.00356	137	178.5	.00560
38	643	.001554	88	278	.00360	138	177.2	.00564
39	627	.001595	89	275	.00364	139	175.9	.00569
40	611	.001636	90	272	.00368	140	174.6	.00573
41	596	.001677	91	269	.00372	141	173.4	.00577
42	582	.001718	92	266	.00376	142	172.2	.00581
43	569	.001759	93	263	.00380	143	171.0	.00585
44	556	.001800	94	260	.00384	144	169.8	.00589
45	543	.001840	95	257	.00389	145	168.6	.00593
46	532	.001881	96	255	.00393	146	167.5	.00597
47	520	.001922	97	252	.00397	147	166.3	.00601
48	509	.001963	98	249.5	.00401	148	165.2	.00605
49	499	.002004	99	247.0	.00405	149	164.1	.00609
50	489	.002045	100	244.5	.00409	150	163.0	.00613

Molecular Weight	1 mg./l. p.p.m.	1 p.p.m. mg./l.	Molecular Weight	1 mg./l. p.p.m.	1 p.p.m. mg./l.	Molecular Weight	1 mg./l. p.p.m.	1 p.p.m. mg./l.
151	161.9	0.00618	201	121.6	0.00822	251	97.4	0.01027
152	160.9	.00622	202	121.0	.00826	252	97.0	.01031
153	159.8	.00626	203	120.4	.00830	253	96.6	.01035
154	158.8	.00630	204	119.9	.00834	254	96.3	.01039
155	157.7	.00634	205	119.3	.00838	255	95.9	.01043
156	156.7	.00638	206	118.7	.00843	256	95.5	.01047
157	155.7	.00642	207	118.1	.00847	257	95.1	.01051
158	154.7	.00646	208	117.5	.00851	258	94.8	.01055
159	153.7	.00650	209	117.0	.00855	259	94.4	.01059
160	152.8	.00654	210	116.4	.00859	260	94.0	.01063
161	151.9	.00658	211	115.9	.00863	261	93.7	.01067
162	150.9	.00663	212	115.3	.00867	262	93.3	.01072
163	150.0	.00667	213	114.8	.00871	263	93.0	.01076
164	149.1	.00671	214	114.3	.00875	264	92.6	.01080
165	148.2	.00675	215	113.7	.00879	265	92.3	.01084
166	147.3	.00679	216	113.2	.00883	266	91.9	.01088
167	146.4	.00683	217	112.7	.00888	267	91.6	.01092
168	145.5	.00687	218	112.2	.00892	268	91.2	.01096
169	144.7	.00691	219	111.6	.00896	269	90.9	.01100
170	143.8	.00695	220	111.1	.00900	270	90.6	.01104
171	143.0	.00699	221	110.6	.00904	271	90.2	.01108
172	142.2	.00703	222	110.1	.00908	272	89.9	.01112
173	141.3	.00708	223	109.6	.00912	273	89.6	.01117
174	140.5	.00712	224	109.2	.00916	274	89.2	.01121
175	139.7	.00716	225	108.7	.00920	275	88.9	.01125
176	138.9	.00720	226	108.2	.00924	276	88.6	.01129
177	138.1	.00724	227	107.7	.00928	277	88.3	.01133
178	137.4	.00728	228	107.2	.00933	278	87.9	.01137
179	136.6	.00732	229	106.8	.00937	279	87.6	.01141
180	135.8	.00736	230	106.3	.00941	280	87.3	.01145
181	135.1	.00740	231	105.8	.00945	281	87.0	.01149
182	134.3	.00744	232	105.4	.00949	282	86.7	.01153
183	133.6	.00748	233	104.9	.00953	283	86.4	.01157
184	132.9	.00753	234	104.5	.00957	284	86.1	.01162
185	132.2	.00757	235	104.0	.00961	285	85.8	.01166
186	131.5	.00761	236	103.6	.00965	286	85.5	.01170
187	130.7	.00765	237	103.2	.00969	287	85.2	.01174
188	130.1	.00769	238	102.7	.00973	288	84.9	.01178
189	129.4	.00773	239	102.3	.00978	289	84.6	.01182
190	128.7	.00777	240	101.9	.00982	290	84.3	.01186
191	128.0	.00781	241	101.5	.00986	291	84.0	.01190
192	127.3	.00785	242	101.0	.00990	292	83.7	.01194
193	126.7	.00789	243	100.6	.00994	293	83.4	.01198
194	126.0	.00793	244	100.2	.00998	294	83.2	.01202
195	125.4	.00798	245	99.8	.01002	295	82.9	.01207
196	124.7	.00802	246	99.4	.01006	296	82.6	.01211
197	124.1	.00806	247	99.0	.01010	297	82.3	.01215
198	123.5	.00810	248	98.6	.01014	298	82.0	.01219
199	122.9	.00814	249	98.2	.01018	299	81.8	.01223
200	122.3	.00818	250	97.8	.01022	300	81.5	.01227

[a] A. C. Fieldner, S. H. Katz, and S. P. Kinney, "Gas Masks for Gases Met in Fighting Fires," *U. S. Bur. Mines, Tech. Paper* No. **248** (1921).

USEFUL EQUIVALENTS AND CONVERSION FACTORS

1 kilometer = 0.6214 mile

1 meter = 3.281 feet

1 centimeter = 0.3937 inch

1 micron = 1/25,400 inch = 40 microinches

1 foot = 30.48 centimeters

1 inch = 25.40 millimeters

1 square foot = 0.0929 square meter

1 square inch = 6.452 square centimeters

1 cubic meter = 35.315 cubic feet

1 cubic foot = 28.32 liters = 0.0283 cubic meter

1 cubic inch = 16.39 cubic centimeters

1 cubic centimeter = 0.0610 cubic inch

1 U. S. gallon = 3.7853 liters

1 U. S. gallon = 231 cubic inches = 0.13368 cubic foot

1 liter = 0.9081 quart (dry)

1 liter = 1.057 quarts (U. S. liquid)

1 cubic foot of water = 62.43 lbs. (4° C.)

1 U. S. gallon of water = 8.345 lbs. (4° C.)

1 kilogram = 2.205 pounds

1 gram = 15.43 grains

1 pound = 453.59 grams

1 ounce (avoir.) = 28.35 grams

1 gram mole of a perfect gas ≈ 24.45 liters (at 25° C. and 760 mm. Hg barometric pressure)

1 atmosphere = 14.7 pounds per square inch

1 foot of water pressure = 0.4335 pound per square inch

1 inch of mercury pressure = 0.4912 pound per square inch

1 BTU = 778 foot-pounds

1 HP = 0.707 BTU per second = 550 foot-pounds per second

To convert degrees centigrade to degrees Fahrenheit: $°C.(9/5) + 32 = °F.$

To convert degrees Fahrenheit to degrees centigrade: $(5/9)(°F. - 32) = °C.$

For solutes in water: 1 mg./l. ≈ 1 p.p.m. (by weight)

Atmospheric contamination: 1 mg./l. ≈ 1 oz./1000 cu. ft. (approx.)

For gases or vapors in air at 25° C. and 760 mm. Hg pressure:

To convert mg./l. to p.p.m. (by volume): mg./l. (24,450/mol. wt.) = p.p.m.

To convert p.p.m. to mg./l.: p.p.m. (mol. wt./24,450) = mg./l.

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Volume I

INDUSTRIAL HYGIENE AND TOXICOLOGY

Volume I

Chapter One

Industrial Hygiene—Retrospect and Prospect

FRANK A. PATTY

Historical accounts down through the ages are replete with allusions to the unattractive lot of the man who has earned his livelihood by manual labor. In ancient times a considerable portion of such work was done by slaves, a practice that has been extended in instances even into the twentieth century. Where slave labor has been employed there has not been sufficient incentive or opportunity to study the adverse effects of occupational environments. Early beliefs that unhealthful conditions are inherent in certain trades have now been disproved and are no longer generally expressed; when plant operators today are presented with clear-cut evidence of unhealthful working environments they are almost universally ready to institute any practical control measures. One of the industries that rather recently joined the modern trend toward providing clean as well as healthful environments was the foundry industry, and even today some foundry operators still believe that considerable dirt, dust, and fumes are inherent in the industry. This is not an expression of conservatism among foundry management, but rather the result of the failure of the layout man, the industrial hygienist, and the ventilation engineer to provide information on the correct design of foundries and foundry equipment as well as on correct ventilation practices. No one wants a dirty work place if it is easy, practical, and economically feasible to have a clean one. Neither does management want to spend huge sums for dust control only to find that it does not do what it was intended to do. Although there may still be isolated employers who regard labor as a commodity purchasable on the market and more easily replaced than preserved, the vast majority of workmen in the United States today are in a very enviable position with respect to the safeguards taken to protect them from occupational diseases and accidents.

I. Historical Résumé

A. MEDICAL AND INDUSTRIAL HYGIENE LITERATURE

Lead poisoning is the oldest recorded occupational disease. Hippocrates, who lived in the fourth century B.C. and is credited with lifting the practice of medicine from its basis of superstition and giving it a scientific foundation, has also been

credited by some with being the first to record adverse effects upon miners and metallurgists from exposure to lead.

Pliny the Elder, in the first century A.D., in his encyclopedia of natural science, refers to the use of bladders that "minium refiners" wore over their faces in an effort to avoid inhaling dust. "Minium" is the Latin word for cinnabar (red mercuric sulfide).

Medical history includes other brief references to occupational exposures, by such ancient authorities as Galen, Celsus, and others. However, it was not until the fifteenth century that further significant progress was recorded. At this time (1473) Ellenbog recognized that the vapors of some metals were dangerous, described the symptoms of industrial poisoning from lead and mercury, and suggested preventive measures. Agricola, a physician and mineralogist, in his *De re metallica* (1556) recognized "asthma" and ulceration of the lungs caused by the inhalation of certain kinds of dust. He stated that among the miners in the Carpathian Mountains some women married as many as seven husbands, each of whom succumbed to this disease.

Philippus Paracelsus (1493–1541), a Swiss chemist, physician, and professor of physics and surgery, with no academic degree, who was thoroughly disliked by the physicians of his time, was credited with being an independent thinker and investigator. He worked in Tyrol as a mining and smelting laborer for ten years, and then several years later returned to the mines, to get material for his treatise on occupational diseases, in which he described various "miners' diseases," disturbances of the lungs, stomach, and intestines, that resulted from digging, smelting, and washing gold, silver, salt, alum, sulfur, lead, copper, zinc, iron, and mercury. He described chronic lung trouble of miners as "lung consumption, asthma, and dyspnea." He attributed the cause to vapors and emanations from the metals and advised that contact with them be avoided, as the condition was incurable.

Paracelsus pointed out fallacies of many medical theories then current, opposed the humoral theory of disease, and taught the use of specific remedies instead of indiscriminate bleeding and purging. Even though he introduced many new medicines, which are still in use today, he was regarded as a charlatan by physicians of his time, and still is in some circles. He died at the age of forty-eight. His untimely death has been variously attributed to "drunken debauchery," to his being thrown down a steep incline by assailants hired by his enemies, to his contracting one of the occupational diseases he had described—perhaps the most plausible cause. His book was not published until 1567, twenty-six years after his death.

Ramazzini, in 1700, published the first book that could be considered a complete treatise on occupational diseases, *De morbis artificum diatriba*. A second and expanded edition appeared (in 1717) in which he discussed not only diseases resulting from exposure to dusts and metal fumes, but also those due to several chemicals. He accurately described, from personal observations, scores of occupations with their attendant hazards and emphasized the necessity for the physician to inquire into the occupation of the patient. So logical were many of his observations that

they remain substantiated today. In the majority of instances, however, the measures he advocated for the control of occupational diseases were therapeutic and curative rather than preventive, a methodology that persists to a certain extent today, albeit in the more progressive circles the control of industrial health is preventive, through hygiene, sanitation, and periodic health examinations.

K. B. Lehmann in his experiments on the toxic effects of gases upon animals instituted a form of research about 1884 that has given us much of the information that serves as a guide for the control of industrial atmospheres today. A French pharmacist and chemist, Jean Baptiste Alphonse Chevallier (1793–1879), contributed liberally to the literature of industrial hygiene.

Many books on the medical and legal aspects of occupational diseases have been published in the last one hundred years, but few deal with industrial toxicology, and even fewer with the preventive engineering aspects of occupational disease control. A list of the more recent and better known books that include some of these subjects is given below:

Health of the Industrial Worker, E. L. Collis and Greenwood (1919)
Industrial Health, G. M. Kober and E. R. Hayhurst (1924)
Industrial Poisons in the United States, Alice Hamilton (1925)
Schädliche Gase, F. Flury and F. Zernik (1931)
Industrial Hygiene for Engineers and Managers, C. P. McCord and F. P. Allen (1931)
The Dermatergoses or Occupational Affections of the Skin, 4th ed. R. Prosser White (1934)
Occupation and Health, International Labor Office (1934)
Industrial Toxicology, Alice Hamilton (1934)
Preventive Medicine and Hygiene, M. J. Rosenau (1935)
Industrial Dust, P. Drinker and T. Hatch (1936)
Industrial Toxicology, Wm. N. McNally (1937)
Toxicology of Industrial Organic Solvents, E. Browning (1937)
Carbon Monoxide Asphyxia, C. K. Drinker (1938)
Toxicology and Hygiene of the Technical Solvents, K. B. Lehmann and F. Flury (1938)
Occupational Diseases of the Skin, L. Schwartz and L. Tulipan (1939)
Analytical Chemistry of Industrial Poisons, Hazards, and Solvents, M. B. Jacobs (1941)
Occupational Diseases, R. T. Johnstone (1942)
Essentials of Industrial Health, C. O. Sappington (1943)
Industrial Medicine, F. J. Wampler (1943)
Manual of Industrial Hygiene, National Institute of Health (1943)
Noxious Gases, Y. Henderson and H. W. Haggard (1943)
A Manual of Pharmacology, T. Sollman (1944)
Introduction to Industrial Medicine, T. Lyle Hazlett (1946)
The Industrial Environment and Its Control, J. M. DallaValle (1947)
Industrial Health Engineering, A. D. Brandt (1947)

B. LABOR LEGISLATION

Labor legislation has played an important part in the progress and development of industrial hygiene, both in the United States and abroad. It is said[1] that the deplorable state of orphaned child workers in English cotton mills was a major

[1] L. B. Chenoweth, W. Machle, and H. Schneider, *Industrial Hygiene*. Crofts, New York, 1938.

factor in motivating reforms in working conditions in factories, and that the initial step was taken by Sir Robert Peel, a millowner, by acquainting the English Parliament with these conditions in 1802. Other reformers became interested. Statistics gathered showed that the average age of the working classes was 22 as compared with an average age of 44 among the wealthier classes, and that the death rate in the workingmen's districts was appreciably higher than the general rate. The Factory Act was passed in 1833, limiting the hours of work of children and providing for factory inspection in certain factories and industries. Several trades were brought under the control of the Factory Act in 1864, and in 1867 the act was broadened to include many industries and those places employing more than 50 persons. This act prohibited the eating of meals in noxious plant atmospheres, provided for the guarding of machinery, and required mechanical ventilation for the control of injurious dusts. Medical inspection of factories was inaugurated in 1897, at which time the idea of compensation was adopted.

France and Germany during the nineteenth century also passed laws to regulate hours of labor and protect workmen in some of the more dangerous trades. Factory inspection was introduced in the United States by Massachusetts in 1877; soon thereafter Massachusetts, New Jersey, New York, Connecticut, Michigan, Missouri, and Minnesota passed laws requiring the removal of dusts and injurious gases by means of exhaust fans.

The United States became the last industrially important country to adopt compensation when in 1908 limited benefits were provided for United States Civil Service employees. New Jersey was the first state to pass such a law, in 1911. Other states followed rapidly in providing compensation for accidents. In 1911 California, Connecticut, Illinois, Michigan, New York, and Wisconsin passed laws requiring the reporting of, and later compensation for, cases of occupational disease. In 1919 Wisconsin made occupational diseases compensable and about half of the states now have laws requiring such compensation. Some of these states recognize only a few specific diseases, whereas others recognize any disease of occupational origin, that is, a disease arising out of or in the course of and peculiar to the occupation. The general coverage law, while it is said by some to be conducive to fraudulent claims that are expensive to refute, is obviously the only completely fair coverage for the workman, whom it presumably is designed to protect. As an example of the obviously unfair situation that can result under the limited coverage statutes, one state, which has been a leader in making occupational diseases compensable, not long ago recognized diseases arising from exposure to "benzine (petroleum products) and its homologues" but did not recognize diseases arising from exposure to benzene (benzol), nor silicosis arising from silica-bearing dusts. Both of these errors have since been corrected. Any fair-minded student of industrial hygiene appreciates the necessity of recognizing and controlling all exposures that adversely affect the health and well-being of employees, regardless of the nature of the exposure.

The first major public act that offered control of an occupational disease in the United States came in 1912 when the use of yellow phosphorus (also called

white phosphorus) in the manufacture of matches was prevented by placing a prohibitive federal tax on its use for that purpose.

What was perhaps the first significant major investigation[2] of occupational disease in this country was undertaken by the United States Public Health Service and the United States Bureau of Mines jointly to determine the cause and extent of pulmonary diseases among lead and zinc miners.

C. SIGNIFICANT EVENTS IN THE PROGRESS OF INDUSTRIAL HYGIENE IN THE UNITED STATES

The first national conference on industrial diseases was called at Chicago in 1910 by the American Association for Labor Legislation, and a commission consisting of representatives of medicine, engineering, and chemistry was assigned the task of investigating the magnitude of the problem and of proposing a method of attack in a warfare against industrial disease. About this time several groups began the study of occupational diseases. The United States Bureau of Mines was created in 1910. The United States Bureau of Labor, set up in 1885, was made the Department of Labor in 1913. This department was charged with collecting "information upon the subject of labor, its relation to capital, the hours of labor, and the earnings of laboring men and women, and also upon the means of promoting their material, social, intellectual, and moral prosperity." The Department of Labor has been responsible for the collection and dissemination of much valuable information in the field of industrial hygiene. There have been attempts by this department either to wrest control of industrial hygiene activities from the United States Public Health Service or to set up a duplicate service. It seems evident that industrial hygiene is primarily a health problem, rather than a labor problem, notwithstanding the fact that a few states have successfully conducted their industrial hygiene activities under state departments of labor. A point upon which there is unanimous agreement is that there should not be an overlapping or duplication of effort by departments of health and labor.

The American Museum of Safety was created in New York in 1911 and later became known as Safety Institute of America, under which name it is still active along educational lines. The National Safety Council was organized in 1913. The American Public Health Association organized a section on Industrial Hygiene in 1914. The United States Public Health Service organized a Division of Industrial Hygiene and Sanitation in 1915. The American Association of Industrial Physicians and Surgeons was organized in 1916. The ill health and increased mortality accompanying the accelerated production of munitions and other war materials for World War I made many persons conscious of the necessity for technical guidance in the recognition and control of occupational diseases. *The Journal of Industrial Hygiene*, which has been the leading publication in the field, was established in 1919.

In 1918 the Harvard Medical School established a Department of Applied Physiology, which in 1922 became a part of the present Harvard School of Public

[2] A. J. Lanza and E. Higgins, *U. S. Bur. Mines Tech. Paper* No. **105** (1915).

Health as the Department of Physiology and the Department of Industrial Hygiene. This was the first time that instruction and research in industrial hygiene leading to advanced degrees had been offered anywhere in the world. This school co-operates with the graduate school of engineering: any of the courses offered in the School of Public Health may be elected by students working for a degree of master or doctor of science in engineering. The School of Public Health, which is open to graduates of schools of medicine, and graduates in arts and sciences with training in basic medical sciences or specialized training and experience in an important phase of public health work, offers the degree of master of public health and, to especially qualified persons, the degree of doctor of public health. The Harvard School of Public Health is one of the few places in the world where any qualified persons may obtain scheduled, broad instruction in industrial hygiene regardless of whether their undergraduate training has been in medicine or in the sciences.

Georgia Technological Institute provides instruction for engineers. Several other institutions offer courses in industrial hygiene—some, in fact most of them, for medical students or graduates only. Many chemists and engineers, as well as physicians, in the field have acquired their specialized industrial hygiene knowledge and skills by association and in the "School of Hard Knocks." Official agencies such as the United States Bureau of Mines, United States Public Health Service, several state divisions of industrial hygiene and a few city health department bureaus of industrial hygiene have furnished valuable training stations for the rounding out of neophytes into full-fledged industrial hygienists.

The National Conference of Governmental Industrial Hygienists was organized in 1938 and has since furnished a valuable forum for the discussion of problems and experiences among this important group of industrial hygienists. The American Medical Association held its first Congress on Industrial Health in 1939. The American Industrial Hygiene Association was also organized in 1939, primarily as a specialized group to encourage and foster the exchange and dissemination of technical information in the basic sciences such as chemistry, physics, mechanical engineering, and toxicology as they apply to industrial hygiene. This organization held its first annual meeting in 1940. It became the nucleus around which industrial hygiene has developed, to be recognized as a scientific profession. Its membership now includes both men and women from the several sciences and medicine that represent the many facets of this particular field of public health. Industrial hygiene has successfully withstood abortive efforts at absorption by both safety engineering and medicine. It borders on each of those fields, but differs in technique from both, and one of its primary functions is to get these two groups to work hand in hand. As long as men of the professional strength that has characterized the field since the early Twenties continue their interest, industrial hygiene will be likely to retain its identity as a separate and important part of public health. It has a specific job to do and the specialized training to do the job—a fact that is constantly becoming more widely recognized. In recent years the American Association of Industrial Physicians and Surgeons, the American Industrial Hygiene Association, and the National

Conference of Governmental Industrial Hygienists have found it to their mutual advantage to hold joint annual meetings and to work closely together, with a pooling of research findings and practical experiences.

Until 1936 the industrial hygiene activities of the United States Public Health Service, compared with present activities, were minor and confined largely to research of a medical and statistical nature. From 1928 until 1932 toxicological research, such as the study of the effects of solvents, vapors, and gases on guinea pigs, rats, rabbits, dogs, and monkeys, as well as the development of the peritoneal injection method for evaluating proliferative action of dusts, was farmed out to the United States Bureau of Mines. Under the able guidance of R. R. Sayers and W. P. Yant this research had become extensive and the Bureau of Mines was hailed by some of the chemical industries as an impartial, qualified research institute where industry could have relative toxicities determined in order that the manufacturer as well as the public might be intelligently guided regarding necessary precautions in the handling and use of chemical products. The studies were co-operative arrangements whereby industry absorbed costs connected with the study of their products. The amount of money involved began to be attractive and protests against "subsidizing" the government and research caused the project to be discontinued. More recently federal funds were made available to the United States Public Health Service through the Social Security Act; whereupon extensive research investigations and a program designed to establish active industrial hygiene units in the health departments of the various industrial states were inaugurated. By 1941 the facilities of the Industrial Hygiene Division, National Institute of Health, of the United States Public Health Service had been greatly extended and the personnel increased from less than a score of persons in 1933 to well over 200. Many of these qualified persons have been loaned to various states to help them establish their own divisions of industrial hygiene, assist in training local personnel, and "sell" the entire field of endeavor to the local officials and population.

Prior to 1936 there were only five state departments of health and three state departments of labor conducting industrial hygiene activities, and these activities were limited. Under the impact of World War II and generous federal grants of funds all the industrial states established industrial hygiene units. In November, 1946, these totaled 52 units, spread over 41 states. The enormous increase in harmful situations along with demands for manpower conservation accompanying World War II made investigational industrial hygiene surveys very much in demand, and led to the hasty training of a number of men for this work. Many of these men had had only rudimentary training in the evaluation of exposures and little or no practical experience in control methods. However, because of, or in spite of, the efforts of this group of novices, and the relatively few seasoned men, industrial health was well promoted during World War II. Industrial health comparisons of munitions workers for 1917–18 and 1941–45, for instance, are very striking.

Other important organizations that have been active in the advancement of industrial hygiene include The American Standards Association; The Industrial

Hygiene Foundation of America Inc.; The John B. Pierce Laboratory of Hygiene, New Haven, Connecticut; The Saranac Laboratories at Saranac Lake, New York; life insurance companies as well as mutual and stock company compensation insurance carriers; and many of the larger private industries. Recently trade unions are evidencing an active interest in industrial health. In 1945 a health institute was opened by the United Automobile Workers (CIO) in Detroit to give diagnostic service to union members. Employees no longer regard x-ray examinations or industrial hygiene surveys with the suspicion that was common a few years earlier. This change of attitude is due in part to improved practices, but mainly to educational successes: in short, the average employee now understands the purpose of such health control work and realizes its value to his well-being. Some states now require pre-employment and periodic medical examinations for persons exposed to potentially harmful materials.

II. World War II and Industrial Hygiene Service

Industrial hygiene procedures have largely passed through the period of inquiry into the causes of ill health and now devote their energies to anticipating and avoiding harmful situations before they have time to cause injury. Many different organizations played a part in this rapid development during the period of rapidly expanded production in 1941–45.

A. OFFICIAL AGENCIES

The Army provided men to make surveys and recommend control measures in Army-owned and Army-operated industrial installations. Similar service was rendered to government-owned, privately operated munitions plants by other government industrial hygiene groups co-operating with the Army. The Navy provided men for its shore establishments, and co-operated with the Maritime Commission in providing service for private shipyards. The United States Public Health Service supplied funds and loaned trained personnel to state and municipal health departments, and also conducted field surveys in industry, especially munitions works. The United States Labor Department concentrated upon activities of an educational nature. The United States Bureau of Mines greatly expanded its health program in relation to mining operations. During and following the period of reconversion to the manufacture of civilian goods many of the trained men who had been active in government agencies were reabsorbed by industry.

B. INSURANCE AND INDUSTRIAL GROUPS

Life insurance and compensation carriers were rather active in the field well before 1941, and they continued their work as best they could with inroads into their personnel occurring from all sides during the war-production years. They are now expanding their activities and re-employing trained men.

During this period industry became much more active in the field than formerly, partly because of a newly awakened interest as a result of state and municipal

activity, partly as a result of organized labor's demands for healthful working environments, partly as a hedge against racketeering, but largely because of a desire on the part of management to make the working environment healthful and attractive, not purely from an altruistic attitude but because management began to realize that the maintenance of a healthful environment pays dividends. More and more industrial concerns have come to the conclusion that industrial hygiene is a necessary adjunct to production and not something to be entrusted entirely to overworked government agencies.

Private institutions, such as, for instance, The Industrial Hygiene Foundation, encountered greatly expanded demands for their services during this period.

C. EDUCATIONAL INSTITUTIONS

Those colleges that had given any organized instruction in industrial hygiene prior to 1940 now provided short courses for greatly expanded classes in an effort to give a large number of interested persons sufficient knowledge to make them useful workers in the field during war-expanded production. During and following this period many medical schools set up short courses in industrial medicine and hygiene as orientation and refresher courses. A few institutions of advanced learning have provided special instruction in health and safety. The present plans include advanced training and education leading to degrees in health and safety engineering, but the opportunities for advanced instruction for chemists, physicists, mechanical engineers, and others who wish to prepare themselves for industrial hygiene engineering are still discouragingly inadequate.

A recent report[3] of the Committee on Professional Education of the American Public Health Association lists Columbia, Harvard, Johns Hopkins, Toronto, Yale, and the state universities of California, Michigan, Minnesota, and North Carolina among the institutions accredited to give the degree of master of public health for the academic year 1946–47. This report recognizes the basic sciences underlying public health practices, including industrial hygiene. Therefore, all graduates of these schools presumably will have received at least a good orientation course in industrial hygiene; some may have an opportunity to prepare for later specialization in it. As the reservoir of competent, experienced industrial hygienists grows, we hope for a greater number of qualified teachers of the subject in order that more students may be encouraged to specialize in the field and thus fill the growing needs of industry and official health and accident control agencies for such specialists.

There has been concurrently a movement to provide advanced courses in technical safety and hygiene for graduates of the arts and sciences independently of any medical or public health schools. The ultimate result of such instruction, if extensive, would be expected to be a merger of safety and industrial hygiene into something yet to be named. That there is opportunity for such academic instruction is apparent but there have been much hesitation, uncertainty, and bickering about its initiation. This has been due in the past to a dearth of suitable text material and

[3] Committee on Professional Education, *Am. J. Pub. Health*, **36**, 244 (1946).

qualified faculty, as well as a division of opinions regarding the scope of the field and the aims to be fulfilled. Here, as elsewhere, there is need for men of foresight who are yet willing to do the spade work necessary to bring to fruition at least part of their vision.

D. RESEARCH ORGANIZATIONS

Much research into the toxicity of materials and into methods of analysis and control of harmful exposures was conducted during the war by the United States Public Health Service, and some by industry. Several industries, seeing the need for such research, made plans to enter the field following the return to peacetime activities. The need for research into the effects of many uncharted forms of air pollution is great. Such work can never expect to keep pace with the manufacturing chemist and the even faster moving physicist, but we can follow more closely than has been done in the past.

III. Industrial Hygiene in Foreign Countries

We have a sketchy and confusing picture of what our neighbors have been doing in industrial hygiene, especially in very recent years. Perhaps the best insight into what European countries are doing in industrial hygiene is given in recent material regarding toxic limits and industrial health in wartime published by the International Labor Office. According to reports the rules and regulations in these countries concerning the use of poisonous materials in industry are based on the results of periodic medical examinations of the workers in plants handling such substances. At certain intervals prescribed by regulations the worker must be examined by a physician. It is the task of the physician to *make an early diagnosis to recognize and evaluate the first signs of absorption of a poison* and if necessary to remove men from work temporarily. The ILO believes that this is a reliable method for the timely detection of endangered workers and also of the hazards in a specific plant.

The shortcomings of such a plan of approach obviously are in evaluating the first sign of absorption—a trick physicians in the United States have not been able to turn to their complete satisfaction. The toxic materials that give rise to recognizable, specific, dependable clinical signs in advance of serious injury are disappointingly few.

The ILO report points to our lack of compulsion in the United States regarding periodic medical examinations. There is little room to doubt that regular and more frequent medical examinations are a desirable way of discovering dangerous exposures, especially in the absence of competent industrial hygiene engineering evaluation and control. When the two methods are properly co-ordinated, however, the most dependable safeguard against harmful exposures is provided.

A. ENGLAND

In England the medical phases of industrial health have received more attention than the more technical and engineering phases of evaluation and control.

Some support for this opinion is seen in the report of foundry experience in recent years.[4] Only 150 sandblasters were engaged in steel foundries prior to the war, yet 31 sandblasters were given certificates covering death, total disablement, or suspension on account of silicosis in the 1932–42 period. Congestion of operations, owing to great demands on capacity, has been credited with increasing the number of silicosis cases by increasing the concentration of dust-producing operations per unit of shop area. A committee appointed to study the situation recommended: (*1*) no silica should be used in parting compounds; (*2*) no sand should be used as an abrasive in "sandblasting"; and (*3*) no person under 18 should work as a sandblaster, in repairing a sandblast plant, or within 20 feet of such a plant. Consideration was given to prohibiting the use of free silica in molding material as well as silica paint on cores. Certain of these regulations appear unnecessarily drastic and do not take into account the possibilities of engineering control.

E. R. A. Merewether, Senior Inspector of Factories in England, recognized this lack of engineering interest and skill when in 1942 he told an American Public Health Association audience that the time had arrived when "the doctor no longer knows everything about everything" and conceded American leadership in industrial hygiene engineering. Merewether recently has attempted to inspire the English chemists to instigate the formation of a society for "the holding of annual conferences and the publication and distribution of papers and literature on the subject of industrial health and safety,"[5] much as is now done by our own American Industrial Hygiene Association and to a limited extent by the American Public Healthr Association.

B. RUSSIA

C.-E. A. Winslow, who visited Russia in 1917 and again in 1936, reports majo advances in public health in that country. Emphasis has been placed on the health of industrial workers. Scientific studies of many occupational hazards and of means of promoting industrial health have been conducted by various research organizations, of which may be mentioned the Institute of Industrial Diseases in Moscow, the Central Institute for Nutrition in Moscow, Pavlov Institute, the Leningrad Institute of Safety, Hygiene and Technique, and States' Scientific Institute of Labor Protection.

The Soviet State has given special attention to questions involving better labor conditions, looking toward the highest possible efficiency and production, as well as the mental and physiological well-being of the workers. Early permissible standards for air pollution in factories tended to be ultraconservative on the side of safety, and rather severe standards for industry to meet. Various motives have been suggested as having contributed to the zeal of industrial hygiene investigators. Recently, however, there have been indications that standards are being revised upward to conform with experience and that in general the requirements have been

[4] "Dust in Steel Foundries," *Engineering* (*London*), **158**, 152 (1944).
[5] *Chem. Age*, **53**, 353 (1945).

made somewhat less rigid.[6] For instance, the maximum limit for carbon monoxide was 0.02 mg. per liter, and is now 0.04 mg. per liter (approximately 35 p.p.m.), methyl alcohol was 0.03 mg. per liter and is now 0.07 mg. per liter (approximately 52 p.p.m.), ethyl alcohol was 1.0 mg. per liter and is now 1.5 mg. per liter (approximately 800 p.p.m.). Amyl and other alcohols, however, that were 1.0 mg. per liter are now 0.5 mg. per liter (approximately 280 p.p.m. amyl alcohol and 330 p.p.m. butyl alcohol). This trend, along with our own general trend downward, indicates that we may possibly reach common ground for some if not most of our thinking in regard to what constitutes a permissible and what a potentially harmful exposure. We have seen good information resulting from research into the control of industrial health in Russia and we expect to see a great deal more in the future. A free exchange of ideas among all countries regarding industrial hygiene is sure to benefit each participant.

C. GERMANY

In Germany in the year 1928 the task of collecting material and making practical observations in industrial hygiene was entrusted to the Medical Committee of the German Society for the Protection of Labor. A literature search was conducted as well as experimental investigations of the most important organic solvents. The Imperial Health Office was established as a clearing house for information regarding chemical composition of solvents and the etiological factors of illness resulting from their use. The inspectors of factories were men with medical training but without engineering training, and as a result, the control measures were largely of a medical nature. It has been stated by one of these factory inspectors that it was easier and more routine to obtain biological specimens, including blood samples, from workmen than to obtain samples of air. Mechanical and engineering measures for the promotion or control of health and safety in industry in Germany have not been notable, but the literature on the results of pharmacological and toxicological investigations, upon which much of our present practice is based, is replete with such names as Flury, Führer, Koelsch, Köster, Lazarew, Lehmann, Müller, Wirth, Zanger, Zernik, and others. Priceless instrumentation, records, and intellect have been reported lost as a result of the war.

D. OTHER COUNTRIES

Australia, Austria, Belgium, Italy, the Netherlands, Spain, Sweden, and Switzerland have contributed to the growing flood of useful literature. South African experience, as reported by Mavrogordata and others, has played a great part in clarifying the etiology of silicosis. South American countries such as Brazil and Argentina are becoming actively interested. China has sent medical men to the United States to study our methods with a view toward the development of industrial hygiene engineering in their country.

[6] A. Metsatunyan, *Hyg. and Sanit.* (*U. S. S. R.*), **10**, 23 (1943).

IV. Industrial Hygiene in the United States

We have seen that the United States lagged behind other countries in providing control measures or compensation for occupational diseases, and that it was not until the late Twenties that industrial hygiene became more than an incipient dream in the minds of a relatively few individuals. A few farsighted pioneers in the field of public health saw the possibilities of making the control of industrial health a vocation and of enlisting the technical aid of professions other than medicine to do the job. Industrial hygiene in the United States has from the start been kept on a high professional plane and has therefore attracted men with a liberal leaning toward technical research.

One of the outstanding reasons that industrial hygiene has been so successful in controlling adverse environmental conditions and in preventing or controlling occupational disease is that pronounced rivalry has developed between the medical men and the men of the sciences, as well as between the scientific professions involved, for instance, chemists and mechanical engineers. This rivalry, as has been pointed out before,[7] has been wholesome and has resulted in advancing accomplishments in the field of industrial health that would have been improbable without it. It is another example of the American way of life, where competition and wholesome incentive have always inspired accomplishments. Advances in industrial process ventilation have been almost solely the achievement of the industrial hygienist: until late in 1945 the heating and ventilating engineers, either from lack of interest or understanding, remained aloof. As a result, many grotesque ventilating systems and ideas have appeared under the sponsorship of sheet-metal men who did not even pretend to understand the physical laws applying to air flow and air movement but were attempting to supply a demand for protection of workmen as best they could.

V. Prospective Roles of Industrial Hygiene

Industrial hygiene has laid aside its swaddling clothes and entered a vigorous stage of advancement. It is no longer seen by industry as the aimless effort of intellectuals collecting bottles filled with nothing so that they can prepare long and useless discourses that few read or understand, or, if they did understand, would know what action to take. The safeguarding of industrial health is on a business basis of evaluation and control and is recognized as such by both labor and management. The purpose of the industrial hygienist is no longer merely to "lock the stable door after the horse has been stolen" but to anticipate and prevent harmful situations, or to control them before serious injury results.

The industrial hygienist has done much toward bringing medicine and safety engineering into close co-operation, partly because his interests overlap these two fields. For instance, the safety engineer looks to the industrial hygienist for assistance in problems involving the technical phases of the flammability or ex-

[7] C. D. Selby, *Am. J. Pub. Health*, **30**, 1422 (1940).

plosibility of solvents, gases, vapors, and dusts. Likewise, the technical differences between the classes of respiratory protection devices and the chemical absorbents used are somewhat confusing and require special study. Medical men with no engineering experience, on the other hand, will be more concerned with the toxicological aspects and in their desire to prevent harmful exposures may consider only the promotion of health without due regard for practical economic measures or the problems of the plant production and maintenance engineers. It is the industrial hygienist's job to become acquainted with these engineers and get the benefit of their reactions to any of his major recommendations so that his control measures will be more sound and acceptable. One of the most urgent needs today is a common understanding between the heating and ventilating engineer and the industrial hygienist. The former thinks in terms of comfort and air conditioning and frequently is unable to grasp the problems involved in the control of gases, vapors, and dusts, which are designated in parts per million or million particles per cubic foot. The industrial hygienist is going to have to take the initiative in getting his control recommendations into terms of volume or rate of flow or something more familiar to the heating and ventilating engineer. He should make it understood more generally that the control of air pollution is something the heating and ventilating engineer needs to become acquainted with and reckon with—not a thing to be added as an afterthought or left to be planned by unskilled persons who may thereby upset the functioning of an otherwise carefully planned heating and ventilating or air-conditioning installation.

Then there are the architects, the plant layout men, and building designers as well as the designers of machine tools and equipment. The basic principles of industrial hygiene must be presented to these men so that industrial hygiene will start with the blueprints of factories and machines. All too frequently still industrial hygiene becomes a matter of telling management what their mistakes have been and how many tremendously expensive changes will have to be made, rather than getting these ideas into design where the most good will be accomplished, easily and cheaply.

In one of the most modern aluminum foundries built during the recent war period, one frequently pointed out as a model of perfection, the mechanization was excellent, the sand-handling and dust-control equipment were good, but some fume, smoke, and heat sources were uncontrolled and the general ventilation left much to be desired. No one had ever made the designer aware that dust- or fume-laden and heated air had to be moved out of any enclosure by removing all of the contaminated or heated air. He had provided ample air supply and exhaust but the inlet and exhaust ports were both in the relatively flat roof and they terminated at the ceiling so that the air at the ceiling was given an ineffectual churning while fumes and smoke from pouring, cooling, and other incidental, unhooded operations were but slowly cleared away. Obviously smoke and fumes should have been removed at their sources and the make-up air should have been distributed at or near the floor level so that contaminated and heated air would have been displaced

upward and exhausted through ports in or near the ceiling. Estimations of the cost of remedying the condition exceeded the cost of the original ventilating system.

Until all schools of higher learning take up the teaching of some of the fundamentals of industrial hygiene in their engineering and other professional courses, the burden of this job will rest on the hygienist. This responsibility applies not only to plant design, but to machine design and plant layout as well. The opportunity to review plans should be sought in an effort to improve design so as to promote the correct application of all control measures, where such has not been done. Not only harmful exposures but also dirty occupations are on the way out. The workingman has come to expect and demand a safe, healthful, and relatively clean and comfortable place to work, and, having once worked in such surroundings, will not readily return to an excessively dangerous or dirty occupation. Widespread shifting of labor during war production resulted in acquainting many workmen with the fact that control of the work environment is possible. Even the foundry has undergone a transmutation from a place with a dirty, dusty, smoke- and fume-filled atmosphere to one of comparative cleanliness. We have some of the cleanest work places in the world here in the United States. We also have some that we do not care to talk about—they are the ones upon which we should focus our attention until they have been cleaned up. American industry is aware of the benefits of more and better production derived from environmental control and health-promotional activities. and needs only to be guided in their application.

Will industrial hygiene engineering be absorbed by either the medical profession or by safety engineering? The idea is not a new one and the answer is in the field of astrology, which to date strangely enough has not been proposed as an essential factor in the promotion of industrial health. Anything can happen and if our educational institutions can turn out doctors of medicine who are accomplished in the sciences of chemistry and mechanical engineering, mathematics, and physics, yet who are willing to do the amount of plain drudgery associated with the engineering phases of the prevention of occupational diseases, then industrial hygiene will surely become the sole province of medicine. If, on the other hand, academic instruction in our engineering and other professional courses allied with this field adequately provides the principles and practice of industrial hygiene and safety, the trend will be toward the development of more competent and highly trained personnel to cover both of the fields now considered separately as industrial hygiene and safety engineering. For such instruction to be successful it must necessarily provide a sufficient period of supervised practice in industry. Graduates of such courses would find common ground and interests with the industrial physician of the future who will appreciate more and more the nature and value of engineering control practices that augment and simplify, in many cases are essential to, his own goal of preventive medicine and hygiene. Regardless of where or how it is taught—in medical schools, engineering schools, colleges, or trade schools—the engineering control of industrial health is sufficiently important to warrant its being placed on the same plane as civil, chemical, or other engineering courses. It

should encompass a well-planned curriculum to include evaluation of the environment, toxicology, pharmacology, physiological effects, control methods including the principles and practice of ventilation, and the correction of all adverse environmental factors—not a course that can be picked up as an afterthought in the last semesters or as a three-month "refresher" course.

Neither of these changes is likely to be brought about overnight or to affect large numbers of persons immediately. Those now in the fields of industrial hygiene or safety who have a broad understanding of their problems need have no concern about such a change. Those who do not have a broad viewpoint should perhaps lose no time in acquiring it or in finding a more dependable future. Meantime we continue as we are. Possibly more schools will choose their students from many professions and direct their instruction to the specialized field of industrial hygiene on the graduate-student level in a manner much as the Harvard School of Public Health has done, with the result that industrial hygiene will probably retain its identity and continue to work co-operatively with the medical and safety groups.

Chapter Two

Industrial Hygiene Records and Reports

JOHN B. LITTLEFIELD

I. Introduction

Records, to be of value, must be concise, but complete, as well as accurate and easily accessible. In gathering and recording industrial hygiene data, the primary objective must be kept in mind: that the records are intended to provide, at some future date, information on the individual and the influence of his working environment upon him from the date he was hired. Another purpose in keeping records is to develop a basis for a statistical analysis of the effect of the environment on groups of individuals, to provide a guide for practical correction of any hazards found.

No one set of forms and records can be adapted to every industrial hygiene organization, although the general ideas are the same. A set of record forms that is ideal for a large plant may prove entirely unsatisfactory for a small plant, or for a company that operates a number of scattered and diversified plants. Insurance companies and state or city industrial hygiene divisions will require special records for correlating their contacts with every type and size of industry.

II. Records of the Environment

The ordinary co-ordinate-ruled notebook makes the best primary record for industrial hygiene surveys: one for field notes; and one for laboratory records, which will also include a concise summary of the field notes. In the field book rough sketches and a brief description of the operation with data as to date, temperature, air movement, clock numbers of men exposed, sampling method, location of samples, sample time, and other pertinent observations may be entered. No additional ruling is needed. A half page or more should be devoted to each sample. For future reference it is very helpful to take a plant drawing and number the spaces between column lines in one direction and letter them in the other so that locations can be easily and definitely identified. The machine number, if available, also should be included among the data. For example, "swing frame grinder No. 147 in Section C-8 Cleaning Room" would locate a sample precisely.

The laboratory notebook should be ruled so that the field data, sample numbers, methods of handling the samples, and results are arranged for ready reference. Samples in each plant, or in larger plants in each department, are numbered consecutively. An example of such a notebook page for dust samples in a foundry survey is illustrated below, on this and the following page.

PLANT: LOCATION:

Sample No.	Date (1944)	Count million per cu. ft.	Department	Description and location	Conditions
102	3/10	7.4	Cleaning	Impinger, Section C-4, 16' N of #2 welding booth; hand grinder on clean manganese steel gear track	Clear, S.W. wind 10 m.p.h. 60° outside, 75° inside, smoky inside
103	3/10	7.6	Cleaning	Impinger, Section C-5, 32' N of #2 welding booth; hand grinder on manganese steel pipe elbow	Same
104	3/10	24.6	Molding	Electric precipitator, molding on floor H-3, main floor, one complete cycle	West wind, 2-3 m.p.h., clear, 55° out, 62° inside
105	3/10	23.0	Molding	Impinger, duplicate of 104 above	Same
106	3/10	38.5	Molding	Electric precipitator, molding on floor D-6, hand molding. Shaking out up-wind on floor E-6	Same
107	3/10	37.7	Molding	Impinger, duplicate of 106 above	Same
108	3/10	6.3	Molding	Electric precipitator, on floor J-3 while pouring 18 750-lb. castings, two per ladle	West wind, 3 m.p.h., cloudy, 53° outside, 84° inside, smoky
109	3/10	7.1	Molding	Impinger sample, duplicate of 108 above	Same
110	3/10	32.3	Molding	Impinger, by operator of sand muller while preparing facing sand, shovels into hopper 860 lbs. sand, 12 lbs. fine clay, 55 lbs. sea coal, 40 lbs. burnt core sand	West wind, 6 m.p.h., 50° outside, 54° inside, very dusty until water is added

After sufficient data on a plant have been collected in this manner, the results for each department and operation may be tabulated in columns on a separate sheet so that average exposures over a year or more can be estimated, fluctuations observed, comparisons made, and so forth. Such year-to-year averages show the results of improvements and changes in operations.

Sample time			Sample vol., cu. ft.	Dilution			Microprojector counts per 0.05 cu. mm.					Total per (0.25 cu. mm.)	Blank	Net count 0.25 cu. mm.
Start	Stop	Min.		Initial ml.	Ratio	Final ml.	1	2	3	4	5			
11:15 AM	11:30 AM	15	1.5	25	-	25	25 23	24 21	20 19	21 22	27 26	117 111	3	111
11:32 AM	11:47 AM	15	1.5	25	-	25	24 21	28 23	23 20	20 25	23 24	118 113	3	113
12:35 PM	12:50 PM	15	39	50	1:25	1250	49 33	41 31	32 34	35 43	40 50	197 191	3	191
12:35 PM	12:50 PM	15	1.5	25	5:25	125	20 12	11 14	15 17	11 11	13 19	70 73	3	69
1:07 PM	1:22 PM	15	39	100	1:25	2500	28 25	26 26	35 33	34 40	29 30	152 154	3	150
1:07 PM	1:22 PM	15	1.5	25	5:25	125	29 17	21 22	19 24	28 26	21 24	118 113	3	113
1:50 PM	2:20 PM	30	78	50	1:25	1250	23 23	15 19	16 21	19 20	19 23	92 106	3	97
1:50 PM	2:20 PM	30	3.0	25	-	25	38 40	44 37	39 38	53 49	46 43	220 207	3	211
3:10 PM	3:25 PM	15	1.5	25	5:25	125	22 20	17 27	15 19	18 21	26 16	98 103	3	97

III. Records of Biological Specimens

When the effect of the environment is measured directly, as by analysis of spot urine samples for lead, a means is provided of correlation of studies of the environment and of the individual. The following is a description of such a survey made in a program for controlling the lead hazard in a brass foundry at some distance from the industrial hygiene laboratory.

Spot samples were collected in the first-aid room at the plant, and the card shown in Figure 1 was filled out and fastened to the bottle with a rubber band.

______________________ COMPANY

MEDICAL DEPARTMENT

Name ______________________ Clock No. ________
(Print - Last name first)

Plant ______________________ Date ______________ 194__

Urine Wasted (Urinate in toilet) ______________________ M
(exact time)

Sample Collected (Urinate in bottle) ______________________ M
(exact time)

Do NOT urinate between time urine is wasted and time sample is collected.

Empty bladder completely into sample bottle (two bottles if needed) when sample is collected.

FIG. 1. Urine sample record.

This card is the result of simplification after first using a three-part slip that had to be filled out with two carbon copies. The first form was abandoned because it required too much time on the part of the plant personnel and was not easily understood. It also required for each sample collected filling in information that was already available to the laboratory even when the first sample had been collected, such as the age of the individual and his working place. Also it had spaces for laboratory data, which were not pertinent to the phase of the survey made at the plant.

Simplicity and explicitness must be the keynote of a form such as this, which is to be filled out by plant personnel. Use of the term "Urine Wasted" had caused some confusion; therefore, the explanation "Urinate in Toilet" was added. The purpose here, to obtain *all* of the urine excreted by the kidneys for a *definite period*

with information as to person, place, and time, is the one and only function of the card.

In the laboratory it is necessary to correlate the data on this card with the volume, analytical procedure (polarographic, dithizone, and so on), and results—information to be retained in the files for a limited period for reference in the event that a question as to the results should arise. A mimeographed columnar form was used and the data entered in pencil, red being used where there was any divergence from the normal technique.

A permanent record of the findings on each individual is kept in the industrial hygiene department, with a duplicate in card form at the plant for the convenience of the local doctor (see Figures 2 and 3). Here all pertinent data on the individual and his environment are assembled, with records of the analyses that show the effect of his environment upon him. The graphic record on the back of the card shows the trend at a glance, whether favorable or unfavorable. With these cards available, statistical analyses can be undertaken and medical control facilitated. For instance, all the individuals in the plant can be segregated into groups for study of the trends in any one department or building or men with different lengths of exposure may be separated for comparison.

As the work of improving the environment progresses, study of these cards affords a means of determining whether—and where—the sampling should be continued and where reduced to quarterly or semiannual intervals. As the results are reviewed each month, any unusual conditions are obvious and the industrial hygienist can take steps at once to find the cause and provide relief.

IV. Interdependence of Medical and Industrial Hygiene Records

The usefulness of an industrial hygiene department is greatly augmented by close collaboration with the medical department, mainly by comparison of records compiled by each. Where an industrial hygiene survey shows high dust counts, comparison of results with chest studies, particularly if there are employees with long service records in the department, can help in determining whether the condition should be attacked as a true occupational disease hazard or as a nuisance hazard. If management is approached with all the facts, hysteria is avoided and better confidence is fostered.

Similar situations develop where medical findings can be elucidated by consideration of industrial hygiene findings. An example was the finding of a high percentage of chests that appeared silicotic in an x-ray survey, but in this case the dust counts were only moderate and the free silica concentration was very low. Further study showed very high concentrations of iron oxide, mainly as fume too small to count, from welding and cutting operations. This pointed to a diagnosis of "possible iron pigmentation" as described in the work of Sander.[1]

Although this discussion concerns industrial hygiene records, it should not be

[1] O. A. Sander, *J. Ind. Hyg. Toxicol.*, **26**, 79–85 (1944).

Plant: X

Clock No: 45 Name: DOE, John Race: White Age: 40 Study No: 2X-100

Department: Foundry - furnace tender Foreman: JONES, John

Description of Working Place: Charges cupola, works on charging platform most of time; exposure to fume from taps below, from pouring in surrounding area, and drossing near cupola. Controlled 4/43 by exhaust hood.

Date of Birth: 4/17/04 Date Hired: 11/12/42

Previous History: Laborer - packing plant. No lead exposure.

Illness Record: 2/25/43 abdominal cramps.

Analysis of Spot Urine Samples

Date	Micro-grams/l.	Micro-grams/hr.	Date	Micro-grams/l.	Micro-grams/hr.	Date	Micro-grams/l.	Micro-grams/hr.
11/20/42	140	6.2	10/22/43	50	3.9			
12/17/42	270	8.6	12/3/43	110	7.1			
1/20/43	360	12.9	1/11/44	90	2.1			
2/23/43	720	30.0	2/15/44	150	No time			
3/23/43	330	12.6	3/1/44	100	9.9			
4/23/43	230	10.1						
5/21/43	140	7.6						
6/30/43	180	9.2						
7/28/43	30	1.0						
9/23/43	180	12.0						

FIG. 2. Urinary lead record.

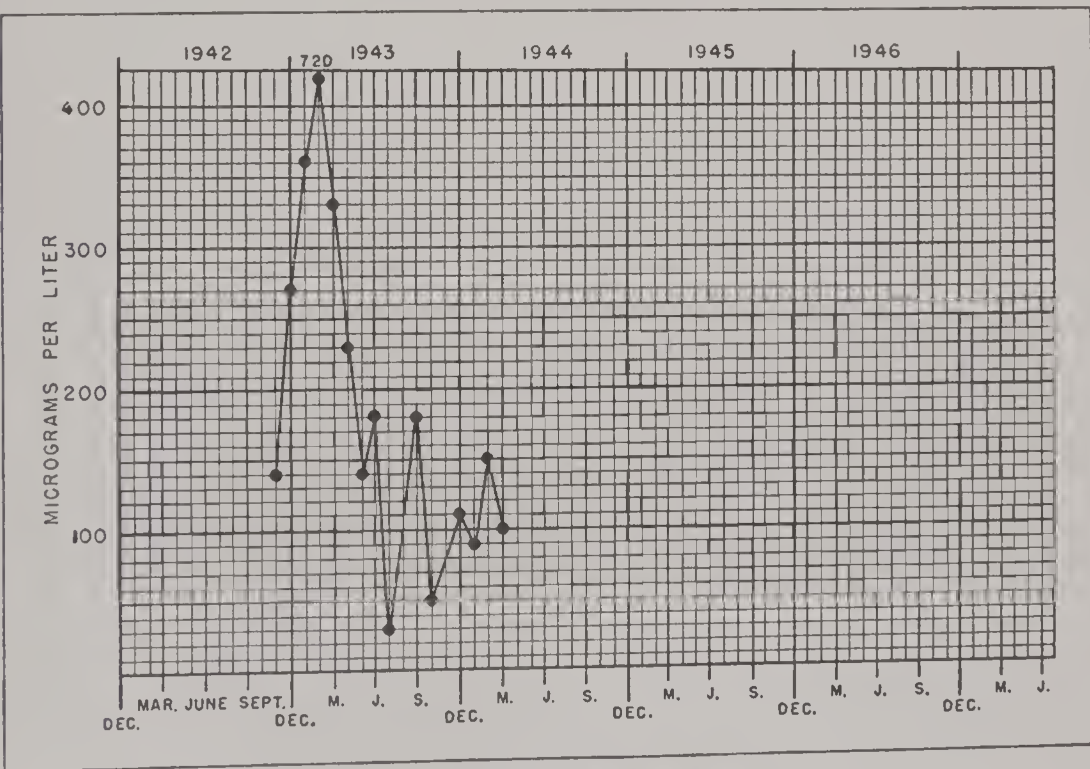

FIG. 3. Graph of urinary lead record.

out of place to mention medical records that are vital to industrial hygiene. The ideal medical program includes a complete pre-employment examination with chest roentgenogram, both of which are repeated at regular intervals in plant surveys. In both, the medical findings with respect to the individual are kept confidential, the information being available only to the medical department and the plant physician. The individual is advised of the results of his examination, but the plant management is not informed.

However, as one of the main objectives of these examinations is the proper placement of the individual in industry, there must be some simple means of advising management where a man may work. One simple way of handling this is by a color card system, an example of which is shown in Figure 4. The card states

PHYSICAL EXAMINATION REPORT

________________ COMPANY

TO SUPERINTENDENT

DIVISION ________________ PLANT ________________

I have this day examined ________________

DATE ________________ STUDY NO ________________

PREEMPLOYMENT ☐

RECHECK ☐

SURVEY ☐

________________ M.D.

Examining Physician's Signature

Form No. 34 Cons.

FIG. 4. Physical examination record.

merely that John Smith was examined on a certain date. If the card returned to the personnel department and thereafter kept in its files is green, the man is physically suitable for any job in the plant. Should the card sent back be yellow, it means that the subject has some defect or handicap that must be considered, and the personnel department is required to discuss the proposed job with the physician and medical department to determine whether the individual may fill it without harm to himself or others. A yellow card in this man's record also means that he may not be transferred without consulting the medical department and obtaining their permission. A man may have a yellow card just temporarily, until some defect is corrected. A red card is returned for men exhibiting serious conditions such as complicated

silicosis, heart disease, uncorrectable vision deficiency, and so on. Applicants getting a red card may not be hired except for work in special nonhazardous situations. Old employees so classified on surveys are treated the same as men with yellow cards and some position is found compatible with their condition.

V. The Nurse's Records

The plant nurse's records are of vital interest to the industrial hygiene department. Every employee's visit to the nurse, whether for actual injuries and re-dressing or for other complaints such as headache, cold, or sore throat should be recorded and recapitulated by department each week or month. A critical review of these records by the industrial hygienist may uncover a previously unsuspected atmospheric contamination, such as carbon monoxide from a defective flue, giving rise to an unusual number of headache complaints from the area affected. Even more obvious is this review as a means of picking up new sources of dermatitis, for as soon as a material that is an active skin irritant is introduced, the nurse will be deluged with complaints. In such acute conditions the alert nurse will call in the industrial hygienist before the situation has gone very far.

VI. Safety Records

Safety and industrial hygiene services in the plant will inevitably overlap, and co-operation between the two is mutually beneficial. Four eyes see more than two, and the safety engineer frequently can call the hygienist's attention to conditions that he (the former) observes in his plant visits. No industrial hygiene survey is complete without a record of safety conditions observed in the course of the work, to be referred to the safety department for its consideration. Each department should be fully informed about the work of the other by exchange of reports and records. This exchange of reports also helps to promote a better understanding among persons working in these closely related fields of endeavor. Where this is not done there is too often a rivalry between these departments as to jurisdiction over certain phases of the work.

VII. Personnel Records

Where the industrial hygiene service is a division of the medical department the personnel records pertinent to the work of this service are readily available. When this is not the case or when special work such as the control of a lead exposure is being conducted, the personnel department can furnish the information on new men essential for the interpretation of the results. At times a new employee may show a high rate of lead excretion that can be explained only by the personnel record of his previous history, which might show that he had been employed in another plant that had a lead exposure.

Labor unions are taking an increasing interest in health conditions and are now including health clauses in their contracts. Copies of such contracts should be

on file with the industrial hygiene department so that a check may be made to see that the plant is kept up to these agreements. It also would be most desirable if the industrial hygienist would sit in on grievance committee meetings to learn of health complaints and to reply to many of them. In this capacity, he can possibly clear up some misunderstandings between labor and management.

VIII. Compensation Claim Records

Compensation claim records are another key to industrial hygiene control, and to be of greatest value should be current and complete. Pertinent data regarding the development of each case through to its final disposition, and including total cost, should be supplied the industrial hygiene laboratory. When thus immediately available to the laboratory, whether company, insurance carrier, or state, technical investigations can be made while facts are fresh to determine the cause of the claim and the means of preventing similar occurrences. These records serve as a guide for trouble-shooting service and are an indicator of problems involved and results achieved. They show where additional control measures are needed, and should be filed under plant or department so that they may be reviewed by the industrial hygienist immediately before a visit to the plant. With tabulations of diseases, substances causing diseases, occupations, industries, years, and cost, they furnish valuable information. However, unless competent men review and investigate these claims and assign correct diagnoses of disease and cause, the records are misleading and worse than useless.

IX. Industrial Hygiene Reports

The industrial hygiene survey report is the medium through which the results of the survey and the recommendations arising therefrom are transmitted to management. This report should include a brief description of the plant or department (unless it succeeds the first of a series on the same subject), the nature of the operations or any significant changes in operations since previous surveys, a discussion of control measures already in operation, tables listing the samples collected and results found, and an interpretation of these results. If available, the results of medical examinations or other findings on the individuals exposed should be correlated with the sample results. Finally, the report should include specific recommendations for control of the hazards found—an industrial hygiene report that includes only criticism of conditions without constructive recommendations is better retained in the hygienist's files. Space should be devoted to a brief summary of observations on housekeeping, on safety, and on employee reaction.

Before leaving the plant the hygienist should go over the report with the plant superintendent or department head. Such a discussion permits the inclusion in the final draft of operating objections to proposed changes and often develops ideas for correction that would not occur to the hygienist alone. It may also disclose any abnormality of operation at the time of the survey that may influence the sample

results one way or another. Should it be necessary to await laboratory findings before preparing a rough draft, this draft should still be discussed with plant men.

The final draft of the industrial hygiene survey report should be addressed to the man in charge of operations, usually the works manager. Copies should be sent to the plant or department head, the chief engineer, the personnel director, and the medical director.

The hygienist will accomplish more in the long run if his reports are not too broad. If he keeps in mind the long-range plan and then drives at one item at a time, he will be more easily understood and arrive at his objective sooner than if he proposes sweeping changes all at once. He should remember the boy with the bundle of sticks: he was not strong enough to break them all at once, but one at a time the task was easy.

CHAPTER THREE

The Industrial Hygiene Survey and Personnel

FRANK A. PATTY

I. Introduction

Industrial hygiene surveys are personal investigations conducted within the premises of an industrial establishment, primarily to determine the nature and extent of any conditions that may adversely affect the well-being of the persons employed. Usually the first result of such a survey is the obtaining of information necessary to the development of engineering and medical control measures for avoiding or eliminating harmful situations.

Industrial hygiene preserves for employed adults their basic capital—health. It is a major problem of the industrial hygienist to maintain and safeguard the physical and mental capacities of workers, and to prolong their productive lives. This is a task of fundamental importance, for bodily impairment makes difficult the building and the maintaining of sound morale.

Ramazzini[1] is the first outstanding industrial hygienist of whom we have a considerable record. His investigations about 1700 A.D. into the causes of occupational diseases were remarkably enlightening. However, like many who came after him, he dwelled at some length upon therapeutic measures for the cure of such diseases, and gave scant consideration to preventing them. Following this early auspicious beginning, it is remarkable that not until the third decade of the present century do we find any widespread realization or acceptance of the next stage in the development of the industrial hygiene survey, that is, the utilizing of engineering methods of control for the actual prevention of disease. Even at such a recent date, industrial hygiene was largely on a complaint-investigation basis: when serious diseases developed, industrial hygiene investigations were undertaken to develop control measures for preventing a recurrence.

The design of the modern industrial hygiene survey is to recognize harmful exposures, and to bring them under control, before workmen experience injury or

[1] B. Ramazzini, *De morbis artificum diatriba*, 1700 and 1713.

evidence any adverse signs or symptoms. This can be done by measuring exposures, evaluating their probable effects by existing toxicological and engineering standards, and utilizing sensitive biological examinations of exposed persons to discover the entrance of harmful materials into the human system in advance of injury. The qualified industrial hygienist recognizes his moral obligation to do his work well. This obligation precludes his accepting responsibilities beyond his capabilities; nor will he allow his findings to be influenced or colored by incompetent persons or selfish interests. The shrewd business man recognizes the value of keeping the industrial hygiene service on such a plane.

II. Types of Surveys

In the practice of industrial hygiene there are four types of surveys: (*1*) the standardized inspection, which deals only with potentialities; (*2*) the preliminary or observational survey, which is a reconnaissance; (*3*) the investigational or appraisement survey, which has as its chief purpose the evaluation and control of existing harmful situations; and (*4*) the combined industrial hygiene and medical survey, which integrates the investigational survey with medical examinations of the workmen.

A. THE INSPECTION SURVEY

The inspection survey is conducted to establish whether or not an investigational survey is necessary. Wherever an investigation has been authorized, or its need established by occupational illness or otherwise, the inspection may be omitted. This survey consists of filling out blank forms or otherwise furnishing data such as the following: name and location of the plant; products manufactured or processed; number of male and female employees; their race; safety supervision; medical and first-aid services; the presence of sick-benefit organizations and availability of accident and sickness records; insurance, if any, for compensation and occupational diseases; the extent of industrial hygiene service available, and utilized, from all sources including the insurance carrier; the operations conducted and the number of employees engaged in each; raw materials, products, and recognized by-products; measures employed for dust, fume, and gas control; and methods of waste disposal. This survey requires little or no technical training in industrial hygiene, and frequently is accomplished by filling in data supplied by the plant management and purchasing agent. Data thus collected can be evaluated for a single plant, or tabulated by industries for a city, community, state, or the country at large. When a large number of plants are involved, the data may be supplied from a representative group of 10 per cent or more, instead of from every industrial establishment concerned. A survey of this sort makes no pretense of being more than a rough indication of potential hazards, as obtained by visual observation or by interviews. It gives little or no insight into actual exposures to harmful materials, nor the suitability or effect of ventilation or other control measures. It is intended only as an indication of the scope of the industrial hygiene problem, and by this means plants

are frequently selected for investigational surveys. One of the important aspects of the inspection survey is a routine check on materials purchased, a most essential factor in the prevention of harmful exposures.

B. THE PRELIMINARY INDUSTRIAL HYGIENE SURVEY

The preliminary or observational industrial hygiene survey is usually the immediate forerunner of a more extensive survey. It is made for the purpose of selecting locations in a plant where exposures or hazards are later to be evaluated by analytical studies in order to determine whether or not additional control is necessary. If no inspection survey has been made, the collection of pertinent data, such as previously mentioned, should now be included. The preliminary survey will also determine the apparatus necessary for the investigational survey. Depending upon the size and complexity of the operations, the time required for the preliminary survey may vary from a few minutes in a small shop to a day or more in large industrial plants. In the smaller plant the preliminary survey may immediately precede the final survey, and both may be accomplished in the same day by the same individual. This preliminary survey is usually made with no equipment other than the five senses—or possibly six. It should be made by a man who is familiar with the type of industry involved, especially the chemistry of its products and by-products, and who is well grounded in the field of industrial hygiene. He may or may not be the man who is to make the final detailed survey, but he should be at least equally familiar with the problems involved in recognizing and evaluating exposures to harmful materials. The survey is best accomplished by following the industrial process through the plant from raw materials to finished products. The industrial hygienist should be accompanied by the production superintendent, or some other qualified plant man, to explain any process or steps in manufacture that are not evident to the surveyor. Among the men who are best suited to the role of guide for the investigator are the production superintendent, the plant engineer, the safety engineer, the plant chemist, and the foreman of the department under investigation. The plant physician or nurse may be able to point out departments that cause trouble. It hardly needs to be stated that a guide, to be of much help to the hygienist, must be prepared to supply or obtain information about any processes involved.

Since the surveyor ordinarily does not use any mechanical equipment at this time, one of his most necessary assets is a well-developed and trained sense of smell. He should be able to recognize and identify all of the common gases and vapors that possess characteristic odors, tastes, or irritant effects, as well as to estimate roughly the concentrations of the majority of them. He should be alert to the personal appearance of the workers, and to any signs that may indicate adverse occupational exposures. This statement is not intended to suggest that nonmedical industrial hygienists should obviously examine the exposed portion of the workman's body for occupational marks or signs, or ask the workman to display such marks. He should not even allow it to be evident that he is making such observations, but at

the same time there is abundant reason why he should keep alert to any indications that a workman may have been exposed to conditions sufficiently adverse to leave a mark or sign. In this way it may be possible to find a serious exposure that might otherwise be overlooked because of the intermittent or obscure nature of its causation. Chapter Twelve discusses at some length the visible signs of industrial diseases, and their possible significance, and points out as well many nonindustrial causes producing similar signs.

Frequently there are contributory operations, or intermittent operations, not in evidence at the time of the survey. These may include preliminary treatment of raw materials, disposal of by-products or waste products, and warehouse operations. The surveyor may learn of these through his experience in the industry, from a knowledge of similar operations, or by an extended discussion with a competent guide. He should always inquire into the location and method of conducting operations of such a nature, as well as into proposed new operations or pilot plant work, where such exist. A most important thing for the surveyor to remember is not to hurry, or be hurried, through a plant but to take sufficient time to give opportunity for recognition of the more obscure situations.

The preliminary survey should determine the presence or absence of control measures, and provide an opinion as to: (*1*) the probable need for, or effectiveness of, control; (*2*) the type of personnel as regards training, skill, or care; and (*3*) the attitude of management, supervising staff, and workmen toward health-control measures. At the end of the preliminary survey it may be desirable to give the management a report of findings and plans. Where an investigational survey is to be made without delay, it may not be necessary to discuss the situation with anyone other than the guide. In any case, having completed the preliminary survey, and decided where all investigations are to be made, the surveyor now selects the necessary equipment and undertakes the final survey.

C. THE INVESTIGATIONAL INDUSTRIAL HYGIENE SURVEY

1. Surveying the Plant

The investigational, or detailed, industrial hygiene survey involves the evaluation of all harmful exposures and the development of control measures. This is what is ordinarily referred to among the profession as an *industrial hygiene survey*. If no previous survey has been made of the plant, it is best to leave any equipment in a safe place and conduct a preliminary survey before undertaking the detailed investigation. It is frequently unnecessary to evaluate exposures by exact measurements. When control is the only objective, and it is obvious to the investigator that contaminants are excessive, he frequently can devise satisfactory control without the benefit of quantitative measurements. However, when there is any question as to the necessity of control, or when facts for record are desired, samples of the atmosphere must be collected and evaluated. In surveys to determine the merits of a claim for compensation for injury allegedly arising from harmful exposure in

industry, it is frequently necessary to obtain quantitative information about exposures in order to establish facts, rather than opinions, even though to the industrial hygienist the exposures may be obviously either insignificant or excessive. Records of periodic analyses of the extent of atmospheric contamination, in any potentially harmful atmosphere, are particularly valuable in evaluating claims presented for occupational diseases alleged to have developed over an extended period of time. In a potentially harmful situation, even though the investigator is completely satisfied that control is ample, sampling may be desirable for its psychological effect: it eliminates personal factors, and gives assurance to the employees of a safe environment. The evaluation survey can well be accomplished with the co-operation of the production superintendent, or the foremen of the particular departments in which investigations are to be made. If the results are to be representative, any air sampling or other quantitative measurements should be made during normal, as well as the most unfavorable, operating conditions and over a sufficient period of time to yield the complete exposure picture. The foremen can assist in maintaining these conditions; and precautions should be taken to avoid arousing the employees' curiosity, not only because of the false conditions created when workmen stop to watch, but also because it may precipitate ill will between employees and management if the impression is given that *harmful materials* may be present in the atmosphere. Since it is a practice in certain industries to pay a bonus for work in hazardous atmospheres where control of atmospheric contamination is difficult, industrial hygiene surveys there should be a matter of routine. If the plant has a physician or a nurse on duty, it is a good policy to visit him or her in order to establish cordial co-operation and to review any records of ill health. The plant physician may wish to accompany the hygienist during his survey of the plant, and this may prove advantageous to both, but it is an exceptional physician who can supply needed information about plant processes.

It is unpardonable conduct on the part of a surveyor to ask an employee suggestive questions such as: Do you feel all right?, Do you get sick often?, Does breathing this atmosphere cause you any discomfort or irritation?. The psychological effects of such questioning, which is only one step short of suggesting to a workman that he is ill, are obvious and undesirable. To some workmen the mere fact that tests for air-borne toxic materials are being made may indicate that dangerous conditions exist, and careless remarks of the investigator may grow to dire proportions and cause needless alarm among the workers. Discussion with employees should be avoided by the industrial hygienist and left to the management or the foreman. Employees in many plants have learned to expect and appreciate the control measures that are the result of the industrial hygienist's work; trade unions have become aware of the benefits to the workmen to be derived from such investigations; while management especially values the savings in materials, men, and efficiency accruing from proper environmental control.

To the direct question "What are you doing?," or "What does that instrument do?," a disarming reply should be given. The industrial hygienist might say that

he is making routine tests, determining ventilation requirements, studying the efficiency of the exhaust system, measuring solvent loss, or he may make some other similar statement of fact. Any remark about measuring the toxic vapors, seeing whether the air will make the workers ill, or seeing whether it is safe to work here would be an ill-considered, and possibly alarming, reply. It is not that the workman should be deceived but rather that he should not be alarmed about something that he probably would not fully understand. There have been instances where women painting dials with radioactive paints have been shunned in the cafeteria, and elsewhere, by other employees who feared they would contract "radium poisoning" by getting too close to them. "Dangerous half truths" are often potent forces in factory personnel relations, as elsewhere, and no industrial hygienist should contribute to their formation. There are, of course, exceptions to the rule against discussions with employees as well as to any other rule, but the fact remains that if industrial hygiene is to accomplish its purpose, a fair attitude must be maintained toward both factory management and the workers. Preservation of the workers' health is always the goal; facts must be reported to management; careless remarks that may instigate false rumors and alarms must be carefully avoided.

When a survey is made solely for the purpose of evaluating and controlling exposures, accuracy may be of secondary importance to speed. It may, therefore, be expedient to employ rapid field methods, even though their results may vary as much as plus or minus 20 per cent from the amount of contaminant actually present in the air. This is especially true of one-day surveys made in localities distant from the central laboratory. The reason for this is obvious since the survey cannot be concluded satisfactorily until the results are known. When the survey may extend over several days or longer, analytical methods requiring laboratory procedures are no serious handicap. In any case, methods and apparatus should never be used in the field by an investigator until he has found them satisfactory in his own use under controlled conditions.

The over-all exposure of an individual can sometimes be more accurately arrived at by analysis of a sample of his urine or blood than by a few samples of air. This is true of exposures to benzene (sulfate ratio), ketones, methanol, probably some of the chlorinated hydrocarbons, acrylonitrile, the fluorides, lead, and possibly other materials.

Air samples may be taken at one or several locations in order to determine individual exposures, general room-air conditions, and sources of contamination. Many variable factors must be considered at the time of sampling, in relation to normal, adverse, and optimal conditions. Single samples, though not to be scorned, should not be accepted as a true indication of existing conditions; because not only does the concentration of contaminants vary from minute to minute, day to day, and season to season, but also errors in sampling and analysis are certain to creep in occasionally even with experienced, and most careful, investigators. The more samples taken, the more evident will be the reasons for any variance in results, trends, peak concentrations, and other factors. There are arguments on each side

of the question of the grab sample versus the extended-time sample; but, except for dusts, there can be no doubt that a large number of properly spaced grab samples tell a more comprehensive story than a single sample taken over the same period of time. Here again, the trained observer, from the senses of smell, taste, or feeling, may be able to evaluate an exposure accurately enough to establish either the necessity for its control or its insignificance. In large measure this depends upon previous observations of known amounts and similar magnitudes of the material to be evaluated, or so to speak, a calibration of individual sensitivity since there is some variation between persons in sense of smell.

All shifts should be observed—the night shift may create an exposure at some operation that the day shift conducts safely or vice versa. Air contaminants should be traced from their origin to the point or points of dispersion, air movements should be studied under normal and adverse conditions, and all unfavorable environmental factors should be evaluated. This evaluation should include temperature and humidity, drafts, illumination, noise, radiant energy, atmospheric dusts, fumes, vapors, fogs, mists, sprays, gases, as well as materials that cause skin afflictions, and any other factors that might adversely affect the health of the workman. It may even be necessary to control an excessive exposure before evaluation can be made of a coexisting minor exposure.

The wise industrial hygienist maintains a proper sense of values and is not unduly influenced by so called "safe limits" and codes that may specify an eight-hour exposure figure and then ignore the time element. For instance, in the case of carbon monoxide, frequently limited by code or "safe limit" tables to 100 p.p.m., to take the attitude that the "permissible" amount should never be exceeded would be a gross error. More properly it should be considered as an average value, because brief exposures to moderately high concentrations of some contaminants that accumulate slowly are entirely acceptable. In a garage, for instance, the exhaust of a car being driven in or out may briefly raise the concentration to well over 500 p.p.m., but if the ventilation is sufficient to reduce this to below 100 p.p.m. within a few minutes, and the concentration does not average above 100 p.p.m., there is no harmful exposure. Scores of materials are in this category. Some of the more common ones are methanol and ethanol, glycols and their ethers, many esters, and in fact practically all of the materials that are highly soluble in water and neither narcotic, irritant, nor immediately toxic at the concentrations involved.

Evaluation and interpretation of findings may require consideration of some of the personal factors in competence and fatigue and the physical appearance of the workmen, as well as their age and sex. Posture at work is recognized as important for the normal individual and should be considered; for the physically handicapped individual it may become of much greater importance. Repeated motion requires special consideration of psychological and physical aptitude. Sanitation in the restaurant and food trucks, the water supply, plumbing cross connections, and the plant sanitary facilities should be carefully considered.

Dermatitis when found to involve a significant number of employees may

require an epidemiological approach in order to evaluate causes or locate an obscure cause. When collecting data for such a statistical study it is best to consider all factors that could possibly have any bearing upon the problem: number exposed, number affected, age, color, sex, complexion, personal cleanliness, opportunities for washing, occupation, department, materials contacted, parts of body affected, description of lesions, length of exposure, precautions observed, control measures used, and their result. A notation should be made of where the workmen eat lunch and smoke or loaf.

During the survey all raw materials, chemical solutions, and solvents warranting attention should be checked for chemical composition, methods of handling, storage, and disposal. Frequently it is desirable to take samples of plant materials to the laboratory for exhaustive chemical analysis in order to find harmful constituents. Although the industrial hygiene survey is primarily concerned with the physiological effects of air contaminants, fire and explosion hazards also should always be recognized. This precaution is desirable because the industrial hygienist is equipped to evaluate the technical problems involved; also, when a fire or explosion hazard can be shown, it may be easy to "sell" a coexistent need for a health-control program. The description of a vapor or dust contamination that may result in blowing up a section of a plant demands attention. Sound business will not permit procrastination on control when convinced that such a situation exists. This kind of response is not always elicited by moderate or borderline health problems. For detailed information on the recognition and control of fire and explosion hazards see Chapter Thirteen.

2. Developing Control of Harmful Situations

Having established the locations where additional control is necessary, the investigator should then devise the proper control methods, such as substitution, isolation, changes in operating technique or ventilation, and their specific application in the plant under study. This does not necessarily mean that where ventilation is the method of choice, he should forthwith compute the engineering data and lay out the details of a complicated ventilation system; but he should be prepared to give advice on the kind and proper application of an exhaust system, along with sufficient information upon basic requirements to enable the plant engineer to design, or obtain a design for, a satisfactory system. To be more specific, he should at least decide between general ventilation and exhaust at the source of contamination, the size, shape, and face velocity requirements of hoods, type of ventilating fan, the necessity of a dust collector, suitable types of dust collector, location of dust collector inside or outside, and the possibility of recirculation of the air. He should be able to understand and use the information in Chapter Ten. On occasion it may prove enormously advantageous to demonstrate by means of sheet metal, plywood, cardboard, or other easily fabricated material how the placing of baffles, or the proper shaping of a hood, can raise the efficiency of an existing exhaust system. The judicious use of a smoke tube, velometer, or other device to locate and

measure air currents and cross drafts may give a clue to where a simple flange or baffle may be placed to direct properly the air flow surrounding a source of contamination, and thereby convert a useless or ineffective exhaust system into an efficient one at little or no cost. The old box-type spray booths without baffles are fertile fields for improvement. The man who can go into a plant that has obsolete ventilating equipment not satisfactorily performing the function for which it was intended and, by directing maintenance and repair work or by placing a few improvised baffles, produce a readily noticeable improvement, will probably have a better reception on his return visit than the fellow who insists upon a completely new and costly installation. This is not an unequivocal approval of the "make it last" doctrine that was forced upon most of us during war times, but there are instances where this approach can be used very advantageously.

The extent to which the investigator may care to go in recommending and designing ventilation will depend largely upon the type of business he is surveying, his mechanical engineering experience and ability, and the policy of his organization. However, any industrial hygiene unit, to operate successfully in controlling industrial exposures, should be able to read and evaluate blueprints of proposed ventilating systems, advise upon their suitability, and offer suggestions for improvement

When personal respiratory protection is needed, the nature and relative amount of contaminant against which protection is desired should be determined and specific recommendations made. A universal-type gas mask should not be recommended for an exposure where another type will give complete and longer protection at less cost. No canister gas mask should be recommended for routine use. Canister gas masks are emergency equipment only, and an untrained person attempting to wear such a gas mask for a prolonged period of work may collapse as a result of its high resistance to breathing.[2] All respiratory equipment should be examined for correct and properly placed canisters, filters, and so on, properly functioning valves, tightness of facepiece, and for leaks

At the end of this investigational survey the hygienist is in possession of an accumulation of facts that must be correctly applied or else they become of academic interest only, and serve little purpose in the promotion or control of health. The hygienist should develop control methods for all exposures, and have them sufficiently crystallized to present to the plant management. Any unusual hazards found during the plant survey should be pointed out to and discussed with the physician or nurse, in order that by co-operation and knowledge of the complete picture both the industrial hygienist and the plant medical department may be aided in their work. The medical director is health officer for the plant, and, as such, it is important that he have knowledge of all information developed as a result of the survey.

At the end of the survey, if not previously done, the plant manager or personnel director, the production superintendent, the safety engineer, and the maintenance engineer should be acquainted with all significant findings along with recommenda-

[2] L. Dautrebande, *Gaz de combat*, Univ. of Liége, Belgium, No. 1, 1935.

tions or suggestions for control. Objections may be raised, some of which can be overcome, whereas others may prove that alternates to some of the original proposals are more practical. It is obviously desirable that any major control program be explained and "sold" by the industrial hygienist to the man who pays for it, the man who supervises its installation, and the man responsible for unimpeded production; otherwise, misunderstandings and objections are almost certain to arise.

The alternative to "selling" the control program is the use of force. Unfortunately the use of force has been overworked and may have been a retarding influence in the promotion of industrial health. The words of a very famous American can well be applied here: "Speak softly and carry a big stick." There are, of course, instances where dangerous conditions exist and where the plant operators neglect or refuse to put through a satisfactory control program unless forced to do so, but these exceptions to the rule should not set the general pattern of relationship. The condition is certainly not improved if some untrained or uninformed representative of an official agency finds an unimportant exposure or potential exposure and, without proper evaluation of conditions, forthwith demands the installation of expensive and unnecessary control equipment. Too often, unnecessarily, his trip may have been followed up by a written order somewhat as follows: "Pursuant to an inspection of your premises you are hereby officially notified to provide exhaust ventilation that will be effective . . . . You are allowed 30 days in which to comply with this order." The informed plant manager who also has at his disposal qualified industrial hygiene service to evaluate properly his exposures and control needs is likely to avail himself of this assistance in order to point out any errors made in control recommendations; and future demands from the offending unit may be immediately met with strong opposition without proper consideration of their soundness. This practice of unnecessary force, referred to above, has not been confined to any group but has been found occasionally in all industrial hygiene groups, federal and state, departments of health and labor, government and insurance, military and civilian. It is to be hoped that the future course will be more toward the educational "selling" of sound control measures, and a curtailment of the use of unnecessary force to get compliance with recommendations. It is further hoped that obviously unsound recommendations will not be presented; that requests for control will be limited to those conditions investigated and weighed by competent, responsible investigators. The "big stick" will prove more effective if reserved for the class of management that fails to understand the necessity for the control of harmful materials, and the value of such control.

3. Records and Reports

There should, of course, always be a written confirmation report of the survey complete with findings and recommendations. This report may vary from a brief unbound typewritten one to a pretentious and voluminous manuscript, in an attractive and expensive binding, depending upon the nature of the relations between the surveyor and the surveyed and whether "dressing" is necessary, as well

as the artistic temperament and literary ability of the surveyor. It is more likely to be read when brief, but should always be sufficiently detailed to establish the necessity for the recommendations presented along with it. Notes should have been made in a field notebook as a permanent record from which to develop the report; the practice of jotting down random bits of information on pieces of scratch paper that may be lost cannot be too strongly condemned. Details if not recorded on the spot are often forgotten; and reports written from memory, though they may be sufficiently accurate in certain instances for control purposes, are almost certainly inadequate for legal record. Unless the original notes, made on the job at the time of the survey, can be produced, any record of atmospheric conditions in a plant offered as evidence in a court may be open to question. It is important that the report of a survey reach the plant management while the situation is fresh in mind, never later than 30 days after the survey and preferably within two weeks. The value of the report is enhanced if it is delivered in person by the surveyor, or this result may be achieved by a personal call as soon as the management has read the report, in time to explain or support any findings or recommendations that may be questioned. Even though a recommendation was agreed upon at the time of the survey, if it arrives at an inopportune time, or tardily enough to have been forgotten or even for interest to have waned, management may assume an antagonistic attitude necessitating another personal contact. Reports or copies of reports should never be presented to other than plant management without the knowledge and permission of the management.

To have to depend upon presenting by mail only the recommendations developed from a survey, and omitting all information pointing to the necessity for each recommendation, is to work under a handicap that will materially lower the percentage of recommendations receiving compliance. To have the recommendations delivered in person, or followed up, by someone who is able neither to discuss them intelligently nor defend them is worse than having no personal contact. Likewise, the more time that elapses between survey and report beyond that necessary for its preparation the lower will be the percentage of recommendations complied with.

D. THE COMBINED INDUSTRIAL HYGIENE AND MEDICAL SURVEY

The combined industrial hygiene and medical survey is the most comprehensive of all industrial hygiene surveys and, depending upon the extent of the study, it usually requires from a few days to a few weeks or even months to complete. In addition to studies of environment and cursory observations of workmen as mentioned previously, this kind of investigation includes studies of individual workmen by medical technicians and physicians; it may include hematological, bacteriological, and parasitological studies as well as physical, x-ray, and other special medical examinations. The interpretation and evaluation of medical information belong in the field of medicine and require the services of physicians qualified by training in each of the above respective fields, or a physician who is closely associated with qualified men in each field upon whose knowledge he can draw. Likewise, engineering

findings and recommendations should be handled by someone thoroughly familiar with the principles involved. The purpose of this combined survey may be to determine the exposure to atmospheric contaminants and any detectably adverse effects upon any of the exposed workmen that such contaminants may have caused; its major goal may be either evaluation or control. The scope may range from a single contaminant in a single plant up to a combination of contaminants throughout an industry. The study may evolve from the discovery of unexplained illness among workmen, or from the presence of contaminants in a workroom atmosphere that have, or are suspected of having, little known or ill-defined, adverse effects.

Our accepted maximum safe limits for atmospheric contaminants have been set by comprehensive studies of this nature, notably those for benzene, carbon monoxide, lead, mercury, and silica-bearing dusts. Needless to say, any such standard "safe limit" is no more accurate than the method employed for air analysis and the concentration data recorded, regardless of how many qualified specialists evaluated the pathology found among workmen. For that reason, in all reports proposing safe working standards the methods of analysis should be explained and substantiated. Later and more dependable, or more sensitive, methods of analysis may throw more light upon the picture and show an accepted figure to be erroneous.

Combined industrial hygiene and medical surveys offer excellent opportunities for public-health research regarding adult health, at least the health of employed adults, and statistics for special groups are often more readily obtained in industry than from other sources. All special conditions obtaining in the industry studied must never be lost sight of, as they might have a bearing upon any general conclusions drawn from the statistics.

III. The Industrial Hygiene Unit

The industrial hygiene unit may vary from the simplest and least pretentious one-man unit to the most elaborate and inclusive unit, represented by the United States Public Health Service, which in its Division of Industrial Hygiene at the National Institute of Health[3] has included a staff of over 200 persons. It is obvious that the small unit is limited in its scope and, therefore, if it is going to accomplish much toward the preservation of health in industry, it must necessarily exert its efforts mainly in preliminary and investigational plant surveys, with almost no time for pure research.

The National Institute of Health, however, in 1943 had a *Research Section* that conducted laboratory research into numerous industrial hygiene problems, a *Dermatoses Investigations Section* to study the occurrence and prevention of occupational skin diseases, and a *States Relations Section*. Medical, engineering, and statistical units served as a source of supply of personnel to the sections: they recruited, trained, and assigned persons to sections for duty. Certain independent studies in the nature of services and research investigations also were carried on.

[3] J. J. Bloomfield, *Manual of Industrial Hygiene*, edited by W. N. Gafafer. Saunders, Philadelphia (1943).

As evidenced by the scope of the publications of this organization, industrial hygiene can be extended to influence practically all branches of community, adult health. All hygiene divisions are in a position to distribute educational information of great benefit in the promotion of industrial health.

State and city industrial hygiene units vary in the number of their personnel from over a score down to the one- or two-man unit. They conduct research to a much smaller extent than the United States Public Health Service, and more recently have expended a considerable proportion of their time in conducting investigational surveys, although in their initial programs a large part of their efforts was spent on inspection surveys dealing with potentialities. The industrial expansion of 1942, 1943, and 1944 with the influx into many fields of relatively inexperienced management, as well as workmen, created an unprecedented demand for investigational surveys in order to minimize losses in man-hours due to ill health resulting from exposure to harmful materials.

There are several types of consultants and several organizations engaged in some form of industrial hygiene practice, ranging from those of an essentially statistical and educational nature to those devoted almost entirely to investigational surveys. The Industrial Hygiene Foundation may be mentioned as an organization having a general, educational, and investigational interest; whereas the industrial hygiene units of insurance companies are principally engaged in investigational surveys and individual control programs. While the primary objective of all industrial hygiene units in private industry is environmental evaluation and control, their activities vary considerably with the type and size of the industry, and the viewpoint of its management. In the larger and more progressive industries there is opportunity for a well-balanced and well-staffed unit with specialists in the different sciences represented, each having a chance to carry on research within his particular field.

IV. Qualifications and Training of Personnel

A. ADMINISTRATIVE INDUSTRIAL HYGIENIST

The necessary qualifications of a director of industrial hygiene have been previously described[4] and the educational qualifications of industrial hygienists discussed.[5] The qualifications here given for an industrial hygiene administrator represent a personal opinion guided by these previous descriptions, and modified by observation and experience.

The director of an industrial hygiene unit must have at least a bachelor's degree from a recognized school and his basic education should be in science or medicine and should include chemistry, toxicology, and engineering. He should have at least five years' training in industrial hygiene with an official health organization,

[4] R. R. Sayers and J. J. Bloomfield, *Am. J. Pub. Health*, **26**, 1087 (1936).

[5] C. D. Selby, H. F. Vaughan, L. D. Bristol, P. Drinker, T. L. Hazlett, and P. A. Neal, *Am. J. Pub. Health*, **31**, 728 (1941).

to include experience in the evaluation and control of exposures to atmospheric contaminants. If he has an M.D. or a Ph.D. from a recognized school and his education included a good representation of such subjects as biochemistry, chemical engineering, mechanical engineering, ventilation, materia medica, pharmacology, physiology, and toxicology, the experience requirements may be reduced to three years.

He should be able to understand and discuss all phases of industrial hygiene and toxicology and be interested in public health and industrial relations. He should be able to set up systems for keeping records of results achieved and for planning future activities. He should be an avid reader and should devise a systematic bibliography of references covering the field of his interests and activities. He should be able to locate the cause of cases of industrial ill health presented by a physician, to make comprehensive analyses of health conditions in industries, to draw adequate conclusions, and to prepare clear and informative reports for publication. He must have tact, courage of his convictions, good judgment, and must be able to address a group. He must do sufficient field work to keep the viewpoint of the man in the field, and it is necessary that he maintain a wide, personal acquaintance with the men active in promoting industrial health. He should support and attend public meetings where current problems in the field are discussed.

B. INDUSTRIAL HYGIENIST

An industrial hygienist should be able to determine the necessity of making specific studies of industrial conditions; to conduct or supervise surveys; to recognize and evaluate harmful conditions; to develop control measures for all adverse situations; to prepare comprehensive reports of findings, with control recommendations; and to present verbally to management, plant physician, maintenance, production, and safety engineers, the necessity and value of control measures.

He should have at least a bachelor's degree from a recognized school, or equivalent training and experience. It is desirable that his basic education and training should include chemistry, toxicology, mechanical engineering, and the principles of illumination, ventilation, and air conditioning. He should be interested in public health, and have at least one year's study in a school of industrial hygiene, or a year of supervised training with a unit of industrial hygiene that included field surveys.

C. OTHER PERSONNEL

The other persons who may be found in the well-staffed units include specialists whose chief qualifications or interests are in some particular part of the field, such as the industrial toxicologist, industrial hygiene physician, industrial hygiene engineer, industrial hygiene chemist, ventilation engineer, analytical chemist, statistician, nurse, technicians, and stenographers. The qualifications and interests of the persons comprising this personnel necessarily will vary widely. While on the one hand the interests of some may cover the entire field, the interests of others may

be very specific. As an example, a man with the basic education of a mechanical engineer may be classified as a ventilation engineer, an industrial hygiene engineer, or an industrial hygienist, depending upon the scope of his activities and interests in the field of industrial health. The same applies to the physician, the chemist, the toxicologist, the physicist, and possibly others. Each may start as a specialist and by association, experience, and study develop interest in and knowledge of the entire field; in which case he may properly lay claim to the title of *industrial hygienist* and, if he wishes to retain identity with his earlier and basic profession, may use that term as a prefix, as engineer, physician, or chemist industrial hygienist.

The term "industrial hygiene engineer" has been used freely and loosely in the past to apply to every individual, not holding a degree in medicine, who aligned himself with, or, in some instances, expressed a desire to align with some industrial hygiene unit. It made little difference whether the individual had ever studied or been associated with any engineering activities so long as he could make some kind of evaluation of atmospheric contamination. Such a man can more properly be called a technician or scientific aide. Unsuccessful attempts have been made to impose the term "sanitarian" upon persons engaged in industrial hygiene work. The connotation of the word suggests dealings with the water supply, sewage, and waste disposal. Although this may be an important part of industrial hygiene, it is not all of it, and therefore the term is not appropriately inclusive and could properly apply only to a specialist in the field, industrial hygiene sanitarian.

The term "etiologist" has been suggested as being more specific, and meaningful, than "industrial hygienist"; but this word applies only to the investigation into causes of disease, and carries no implication of ability to devise and apply correct control measures. Since the industrial hygiene survey report that does not include suggestions or recommendations for the control of any unhealthful conditions found has a disappointingly flat flavor, the *industrial hygienist* must be more than an etiologist.

CHAPTER FOUR

Personal Factors in Competence and Fatigue*

JOSEF BROZEK

I. General Principles

The tremendous and continuing increase in productive proficiency witnessed over the last 150 years has been due primarily to improvement in tools and machines. One of the essential characteristics of the Industrial Revolution was the relentless effort of inventors and mechanical engineers to lower the physical exertion and skills required by factory jobs. The skill of an individual worker, measured in terms of manipulative dexterity, experienced judgment, and particularly in terms of versatility in performing a number of operations, has undoubtedly decreased. The operation of a machine tender, for whom the equipment is set up and repaired by a specialist, is the "ideal" of mechanized production. This type of job exemplifies clearly an important human aspect of industrial development, the transfer of the skills of the workman to the machine.[1]

In terms of straight output the contribution of the study of the human factor in industry is in general much smaller than the contribution of industrial technology. The degree to which man directly participates in the process of production varies widely from job to job. It is significant enough to attract the attention of the production engineer, who attempts to increase the effectiveness of the "human motor" by developing the discipline of motion and time study.[2] The industrial psychologist directs attention to the fact that with all the emphasis on uniformity of machines and of workers' motions, there are significant differences in the amount and quality of output of the individual workers,[3] unless the individual differences in work capacity are masked by superimposed *social pressure* for a uniform output. That also is a human element. One of the important jobs for the students of the human factor in industry is to determine which of the measurable human characteristics—

* From the Laboratory of Physiological Hygiene, University of Minnesota, Minneapolis.
[1] C. A. Koepke, *Plant Production Control.* Wiley, New York, 1941.
[2] R. M. Barnes, *Motion and Time Study.* Wiley, New York, 1940.
[3] J. Tiffin, *Industrial Psychology.* 2nd ed., Prentice-Hall, New York, 1947.

anthropometric, physiological, and psychological—are related to the differences in industrial performance.

Improvement of the various aspects of working conditions such as lighting, temperature, noise control, and so on, will be reflected directly in increased output records only in those operations in which the human factor plays a direct and significant part. For example, one can expect most dramatic increases in output as a result of improved lighting in such operations as inspection. In operations in which the work does not involve precise and fast perception of detail the direct gain from improved lighting cannot be great. Yet improvement in workers' morale and increase of job satisfaction, reflected in diminished labor turnover, absenteeism, and industrial unrest, represent real economic as well as human gains.[4]

In studying the complex problems of industrial efficiency one must consider the interrelationships between work and health of the worker. The medical officer in industry has the opportunity and the duty to see the problem of health in all its ramifications, a position comparable only to that of a military medical officer. "Health" is defined not only, negatively, as an absence of disease: it involves also, positively, occupational fitness, an effective and continued participation in the industrial enterprise.

In the development of industrial medicine one can roughly distinguish three main periods. In the first the treatment of wounds resulting from industrial accidents absorbed most of the time; industrial medicine was practically an equivalent of traumatic surgery. In the second period attention was focused on prevention of accidents and of occupational diseases. In the third period, on the threshold of which we stand today, industrial medicine will broaden its scope still further: "It will promote individual physical and mental hygiene, institute nutritional guidance, sustain athletic endeavors, prescribe periods of rest, and aid management in selecting the proper employee for each specific task."[5] Periodic re-examinations of employees will provide a basis for effective health service. This should extend into the home of the worker and be co-ordinated with the public health program of the community.

The broadening of industrial medicine has its parallel in the somatopsychosocial orientation of human biology.[6] The growth of psychosomatic medicine with its emphasis on the physiological and pathological effects of emotions is one aspect of this trend.[7] The human being represents an "individual," not divisible into a body separated from the mind, separated in its turn from the social milieu. What we continue to call mind is "but one aspect of the functioning of the physical organism . . . an abstraction which summarizes the manner in which the individual as a whole reacts to his environment, that environment consisting of his physical body, his

[4] M. S. Viteles, *Industrial Psychology*. Norton, New York, 1932.

[5] R. T. Johnstone, in *Rehabilitation of the War Injured*. Philosophical Library, New York, 1943.

[6] L. K. Frank, *Sci. Monthly*, **56**, 344 (1943).

[7] E. Weiss and O. S. English, *Psychosomatic Medicine*. Saunders, Philadelphia, 1943.

previous experiences, the climatic and other physical conditions surrounding it, and the conduct and attitude of his fellow men."[8]

The labeling of the components of human work as "physiological," "psychological," and "sociological" is to some degree arbitrary. The fact that we have a physiological psychology and a social psychology indicates the indistinctness of the fringes of the three sciences and the actual continuity and merging of the borderline problems.

A realistic study and handling of complex personality problems requires participation of a group of specialists. In the diagnostic work of the Occupational Analysis Clinic of the Employment Stabilization Research Institute, University of Minnesota, a physician, a psychologist, and a social worker shared the responsibility for the characterization of clients by obtaining and interpreting information about health and physical fitness, abilities (verbal, clerical, manual, mechanical), personality characteristics, occupational interests, educational background, work history, and family history. The economist and the industrial engineer were at hand when their judgment was needed.[9]

The pioneering research on personal factors affecting work efficiency in a large mercantile establishment was carried out "by a group of psychiatrists, psychologists, and psychiatric social workers, organized into a well-integrated unit and approaching these issues from a broad clinical and social case angle, as well as laboratory viewpoint."[10] The combination of the skills covering general medicine and psychiatry, psychology, and social research and service was regarded as the minimum basis for an adequate diagnosis and treatment of work maladjustment. Because the "job behavior study" is an integral and important part of the diagnostic program, a close contact with the supervisors is important. Also, success of the therapy often depends on the supervisors' intelligent co-operation with the group of personnel specialists.

One of the most outstanding characteristics of the well-known research on human aspects of industrial efficiency, carried out at the Hawthorne plant of Western Electric Company,[11] was the passage from an intensive study of the characteristics of the individual worker and his "material" environment (e. g., lighting) to the study of his "social" environment, the relations between individuals, and particularly the effects of the informally organized groups of workers. The dynamics of social behavior became the center of interest.[12]

The sociologist views an industrial organization as consisting of individuals (and groups of individuals) in interaction. To him the problems of harmonious human relations are an integral part of the study of personal factors in industry.

[8] W. Overholser, in E. J. Stieglitz, *Geriatric Medicine.* Saunders, Philadelphia, 1943.

[9] D. G. Paterson and J. G. Darley, *Men, Women and Jobs, a Study in Human Engineering.* Univ. Minnesota Press, Minneapolis, 1936.

[10] V. V. Anderson, *Psychiatry in Industry.* Harper, New York, 1929.

[11] F. J. Roethlisberger and W. J. Dickson, *Management and the Worker.* Harvard Univ. Press, Cambridge, Mass., 1940.

[12] E. Mayo, *Personnel*, **17**, 264 (1941).

The dependence of efficient production on a well-timed sequence of industrial operations, with the assembly line as the acme of a tightly knit organization, received much attention from the production men. The facts and effects of the social interdependence were studied to a considerably smaller extent. Yet industrial organizations are not made up of only the technological system of organized work routines but include also the ways in which people work together, the teamwork of the men in the department, the teamwork of labor and management.[13]

The interplay of the impersonal (physical), personal (psychological), and interpersonal (social) factors is very complex. Thus an individual's dissatisfaction with work can be related to a physically uncomfortable work environment or to a lack of "belonging" to the group. On the other hand, the emotional distress can manifest itself in somatic symptoms such as tics, epigastric pain, or circulatory disturbances; in psychological symptoms such as phobias or hysterical behavior; and in interpersonal symptoms such as aggression against the fellow workers.[14]

From the systematic point of view, the study of the human factor in industry can be made with reference to two main tasks: selection of workers and maintenance of an efficient labor force. The problems are interrelated; careful selection and placement will reduce the number and magnitude of the maintenance problems. The problem of fatigue is related to both topics; it is important enough to be treated in a separate section. The material will be presented under the following headings: problems of selection, problems of fatigue, and problems of maintenance.

The chapter does not fill the acute need for a comprehensive survey of methods and results of the science of human work. Such a survey should incorporate the results of the extensive British, Russian, German, and French industrial investigations and present in an integrated manner the contributions of mechanical engineering, physiology, medicine, psychology, psychiatry, and sociology. Ergology, the complex science of human work, has a truly interdisciplinary character[15] and its problems should be treated on a broad, co-operative basis.

II. Problems of Selection

A complete employment examination includes evaluation of the application blank and of the personal recommendations and reports about the applicant, a preliminary interview, general physical health examination, general psychological examination, special tests of vocational fitness, and a final interview.

In the task of selecting men and women for industrial work the specificity of the job demands should always be kept in mind. When selecting workers for heavy manual labor, the physiological and biochemical tests determining changes in cardiovascular, respiratory, and metabolic functions in hard work may play a significant role. The psychomotor characteristics are important for light manipulative tasks. In some jobs the visual functions are the critical components of work

[13] E. D. Chapple, *Applied Anthropology*, **1**, 2 (1941).
[14] M. Rosenbaum and J. Romano, *Am. J. Psychiat.*, **100**, 314 (1943).
[15] J. Brozek and A. Keys, *Am. Scientist*, **33**, 103 (1945).

performance. In selecting applicants for executive and sales positions the emphasis must be placed on the "personality" characteristics.

A. PHYSICAL FACTORS

In dealing with the physical aspects of human work we have the twofold task of: (*1*) analyzing the physical *demands* of the job on the worker and (*2*) appraising the physical *capacities* of men considered for the job. Significant work in the first area has been done in the last decade by the Division of Occupational Analysis, first under United States Employment Service and later as part of the War Manpower Commission.[16] The work was initiated in connection with the attempts to develop methods for a more adequate placement of the physically handicapped. Between 1941 and 1943 a number of bulletins were issued listing jobs considered suitable for workers with such physical limitations as orthopedic disabilities or blindness.

The technique of determining and matching the physical characteristics of the job and of the worker was applied extensively during the war in the shipbuilding industry.[17] This matching of job and worker was a co-operative project of the regional and Washington personnel of the War Manpower Commission, the Kaiser Shipyards in Richmond, and the staff of the Permanente Foundation Hospitals in Oakland and Richmond, California. The physical demands were expressed in terms of the activities of the worker on the job, such as lifting, and in terms of environmental conditions under which the job is carried out. The work environment is characterized in terms both "physical" (work in wet quarters) and "human" (work alone, around others, with others). The job analyst checks, on the standard Physical Demands Analysis Form, which factors are required by the job, and he describes in a simple narrative form in greater detail the factors involved. In giving the details of environmental conditions, the analyst indicates also the hazards inherent in working in a given job environment.

The description of the job of a carpenter helper may be taken as an example of the way in which the results of the Physical Demands Analysis are presented[17] in Table 1. The Physical Capacities Analysis Form contains the same categories as the Physical Demands Analysis Form and is filled out by the physician on the basis of a physical examination and other clinical information available. The physician marks whether the employee has full, partial, or no capacity to do work involving the activities and environmental conditions mentioned in the form. For partial capacity the permissible work is specified in detail, for example . . . "may intermittently climb up and down ramps, stairs, ladders up to —% of work period." Only these recommendations, not the diagnosis, are available to the placement officer. The process of matching capacities with the job demands is facilitated by the section on "job titles, job locations, and job families,"[17] which summarizes the

[16] Staff, Division of Occupational Analysis and Manning Tables, *Occupations*, **22**, 387 (1944).

[17] *Physical Demands and Capacities Analysis.* Permanente Foundation, Oakland, Calif.

TABLE 1

Physical Demands Analysis for the Job of Carpenter Helper[17]

Physical factors			Environmental factors		
X	1	Lifting	X	51	Inside
X	2	Carrying	X	52	Outside
X	3	Handling		53	High temperature
X	4	Pushing		54	Low temperature
X	5	Pulling		55	Sudden temperature changes
X	6	Climbing		56	High humidity
	7	Jumping		57	Low humidity
	8	Running	X	58	Toxic conditions
X	9	Walking	X	59	Radiant energy
X	10	Standing	X	60	Moving objects
X	11	Stooping	X	61	Mechanical hazards
X	12	Crouching		62	Electrical hazards
	13	Kneeling		63	Exposure to burns
	14	Crawling		64	Explosives
	15	Twisting		65	Vibration
	16	Reclining	X	66	Noise
	17	Sitting	X	67	High places
X	18	Reaching		68	Cramped quarters
	19	Fingering	X	69	Wet quarters
	20	Feeling	X	70	Working with others
X	21	Talking	X	71	Working around others
X	22	Hearing		72	Working alone
X	23	Seeing	X	73	Day shift
	24	Color vision	X	74	Swing shift
	25	Depth perception	X	75	Graveyard shift
	26			76	
	27			77	
	28			78	

(X = required by job)

Details of Physical Factors: Walks about 500 feet between shops and hulls and climbs about 50 feet up and down ramps and stairs about 12 times daily, half the time carrying tools and materials weighing up to 25 pounds (40%). Intermittently climbs to and from staging 4 feet high, and stands, stoops, crouches and reaches above and below shoulder height to grasp, lift and handle materials weighing up to 25 pounds, and to position materials by pushing and pulling in all directions while assisting Joiner (35%). Walks and stands about shops while orders are being filled (25%). Must be able to discuss work with others, and to see ruler graduations of $\frac{1}{16}$ inch. Physical factors similar on all shifts.

Details of Environmental Factors: Works all shifts, with and around others (100%), inside (60%), outside in all weather (40%), and on staging 4 feet high (10%). Exposed to sawdust particles (25%), to liquids, vapors and odors of zinc chromate primer, paint and thinner (25%), to rays from electric welding arcs (30%), to materials carried by cranes (40%), to materials carried and accidentally dropped by other workers (100%), to traffic hazards (40%), to sharp edges of materials (100%), to hoses and materials on decks (50%), and to nearby chipping and hammering

physical demands in the shipbuilding industry, with similar jobs grouped together. When a carpenter working on the hulls at the outfitting dock, has sustained an injury necessitating amputation of one leg above the ankle and cannot go back to his work, he is still able to do a number of jobs in which his skills as a carpenter would be utilized and which would not require "climbing, jumping, running or working in wet quarters," contraindicated by the physician.

The development of techniques for determining physical demands of a job has made a greater progress than has the skilled appraisal of physical capacities and of the degree of their limitation in the handicapped. The fact that both the job demands and worker capacities are expressed in the same terms is of practical importance as it provides a common frame of reference for the job analyst, the industrial physician, and the placement officer. Also, the positive approach, the emphasis on what the worker *can* do rather than on his limitations, and the confidential doctor-patient relationship are desirable features of the program. But the recommendations must be *based* on a sound diagnosis, and it is in this area that the use of objective quantitative techniques for the study of the cardiovascular, respiratory, metabolic, neuromuscular, and sensory aspects of "fitness"[18] should supplement the typical clinical descriptions of existent pathologies.

It is expected that specific recommendations, such as "may lift and carry up to 25 pounds 6 times per hour" in a case of cardiac disability, would gain if standard work tests were included as a part of the diagnostic procedure. At present, after the physician has decided that a worker is limited in his capacity to lift and carry, he indicates in the form "the maximum number of pounds and the maximum number of times per hour which the physician *believes* (italics ours) the worker has capacity for lifting and carrying." There are no data to back the statement that "the figures are subject to a 10 per cent variation which is approximately as accurate as these physical factors can be estimated."[17] If the quantitative recommendations were based on quantitative indices of cardiovascular capacity, the concept of the "margin of safety" would be placed on a firmer ground. We wish to emphasize that this is not to replace a skillful clinical judgment but to broaden the basis for an intelligent interpretation of the clinical picture in terms of vocational fitness.

In Kaiser Shipyards the analysis of the physical capacities is limited to *replacement* of workers partially disabled as a result of illness or injury. The fact that *preplacement* physical examinations are excluded by a clause in the labor union

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noises (25%). Environmental factors similar on all shifts.

Details of Hazards: Possibility of illness from exposure during wet weather (40%), of injury from falling as far as 8 feet down stairs and from staging (10%), of eye and respiratory irritations from sawdust particles (25%), of respiratory, digestive and skin irritations from zinc chromate primer, paint and thinner (25%), of injury to the eyes from rays from electric welding arcs (30%), of being struck and injured by materials carried by cranes (40%), of being struck and injured by materials carried or accidentally dropped by other workers (100%), of injury from traffic accidents (40%), of cuts from sharp edges of materials (100%), of injury from falling over hoses and materials on decks (50%), and of impairment of hearing from nearby chipping and hammering noises (25%). Hazards similar on all shifts.

[18] H. L. Taylor and J. Brozek, *Federation Proc.*, 3, 216 (1944).

contracts indicates a general, deplorably low level of understanding for scientific approach to human work in industry and lack of confidence in its ethical administration. Thus the fact and fable of employers' misusing the medium of physical examinations to get rid of men active in organizing the labor unions seriously handicaps the application of techniques that would not only decrease—through selective placement—the risk of the employer but also significantly enhance the health of the worker.

B. PSYCHOLOGICAL FACTORS

Men concerned with the optimal utilization of manpower are beginning to realize more clearly than formerly the need for placement of the workers in accordance with individual physical as well as mental capacities. In order to determine how extensively employment testing is used in American industry a brief questionnaire on employment procedures was sent to the members of the Personnel Division of the American Management Association.[19] The firms that responded were regarded as approximately representative of American business: 69 per cent of the returns came from manufacturing companies, 11 per cent from banking and insurance organizations, 9 per cent from food and trade fields, 8 per cent from transportation and communication companies, 3 per cent were unclassified. The number of employees per organization varied from 50 to over 20,000, with an average around 2000. Out of the 147 companies, a total of 94 reported use of tests; 77 used tests for plant workers, 90 for office workers, 35 for salesmen, and 49 for supervisors. The relative frequency with which various types of tests were used for the four occupational categories is indicated in Table 2.

TABLE 2

Frequency of Use of Various Types of Employment Tests as Percentage of the Total Number of Firms Using Tests[19]

Type of test	Occupational group			
	Plant workers	Office workers	Salesmen	Supervisors
Intelligence	40	57	29	35
Aptitude	44	38	29	16
Personality	16	18	31	31
Interest	8	11	17	16
Proficiency	34	53	14	20
Not specified	8	3	14	8

The use of employment testing in industry was definitely intensified by the wartime needs for hiring large numbers of new workers[20] and this impetus has largely carried over into peacetime. Of particular value to business and industry may be experience obtained in such war activities as the civilian testing in the

[19] P. S. Achilles, *Personnel*, **19**, 609 (1943).
[20] H. Borow, *J. Consult. Psychol.*, **8**, 70 (1944)

Quartermaster Corps.[21] The testing program included the following points: (*1*) selection of specific test batteries set up for job classes or specific jobs; (*2*) administration, scoring, and interpretation of the tests given in connection with the service done for the Placement Branch, the Training Branch, and the Employee Relations Branch; (*3*) provision of reports and maintenance of records; (*4*) conducting of research necessary for the establishment of local norms and determination of the validity of tests used experimentally. Testing was just one aspect of the Civilian Personnel program in the Quartermaster Corps and was co-ordinated with other personnel activities. The value of tests was summarized as follows: "Tests used wisely and with due consideration to their limitations enable the immediate location of the more apt workers and more trainable employees. Tests are making an important and vital contribution to the war effort by insuring the maximum utilization of manpower."[21]

The administration of standard psychological tests appears very simple. This simplicity is largely deceiving. Performance tests are meaningless unless the examiner is able to create an atmosphere of optimal motivation. The creationof this atmosphere is a particularly delicate task when one examines, in the process of validating a test, a group of men already employed on the job. The validation of selection tools, an indispensable part of every sound testing program, as well as the improvement of the existing tests and development of new instruments, is a technical job and should be handled by competent men. When the industrial testing in a smaller plant is being set up by an outside agency, care must be taken to obtain consultants of professional caliber.

It is not feasible to attempt a comprehensive survey of psychological employment procedures and their results. The information has been summarized by Burtt[22] and by others. An up-to-date annotated bibliography of employment tests used in industry and business was prepared by Benjamin.[23] In addition to books and pamphlets on the general topic, it lists materials concerning specific types of tests: aptitude tests for industrial and clerical jobs, trade tests, tests of intelligence, of interests and personality, and of accident proneness. It also includes reports of research on the application of tests and reports of company experience with their testing programs. Another useful bibliography was compiled by Cronbach.[24] It considers not only the problem of selection tests and of rating, but also other fields into which employment psychology has expanded, including job satisfaction and problems of motivation, labor relations, group morale, leadership in industry, and handling of personality problems. It has special sections on woman power, training, and environmental and physiological influences.

[21] W. C. Kvarauceus, W. N. Durost, and R. F. McClellan, *Educ. Psychol. Measurement*, **5**, 17 (1945).

[22] H. E. Burtt, *Principles of Employment Psychology*. Harper, New York, 1942.

[23] H. C. Benjamin, *Employment Tests in Industry and Business: A Selected, Annotated Bibliography*. Princeton Univ. Press, 1945.

[24] L. J. Cronbach, *Manpower Psychology: An Annotated Bibliography*. State College of Washington, 1943.

In presenting the psychological factors and techniques in selection we shall limit ourselves to general aspects and illustrative examples.

1. Interview

The interview will always remain an important part of employment procedures. The interview technique[25] serves particularly well in the evaluation of those personality traits for which the present tests and inventories are inadequate. The traditional employment interview was apt to be a disconnected discussion, without direction and definite content. The procedure differed from interviewer to interviewer and resulted in a general, vague impression of the candidate. Such circumstances considerably impeded a systematic statistical validation of this selection technique.

With only a short time available for individual interviews, attempts have been made to increase the efficiency of this widely used selective procedure. Although the "free" or undirected interview may be essential for interviewing men for positions involving social contacts and requiring verbal facility, for most jobs some degree of standardization of the interview is desirable. The interview usually covers three distinct areas: (*1*) personal history, including family background, education, and work experience; (*2*) job knowledge; and (*3*) personality characteristics, in the broad sense, from appearance and manner to intelligence and leadership capacity.

In order to overcome some of the inadequacies of the traditional employment interviews, Hovland and Wonderlic[26] developed a set of standardized interview questions, the responses to which are evaluated by means of ratings that add up to give a total score. The items are marked "plus" when considered as indicating success on the job and "minus" when prognosticating failure. The Diagnostic Interviewer's Guide, as the instrument is referred to by its authors, covers the following four points:

(*1*) Work history — employment stability, job satisfaction, ability to comprehend the assigned tasks, ability to profit by previous work experience. (*2*) Family history and social, economic, and educational background. (*3*) Social history — ability to get along with people, avocational interests. (*4*) Personal history — life goals, reasons for applying for this particular job.

When twenty-three individuals were interviewed locally by one interviewer and subsequently at the headquarters of the company by another interviewer, the total scores obtained in the two interviews correlated 0.71. As the interview was given only to applicants who had passed a preliminary interview and the psychological tests, the range of scores is restricted and thus the correlation coefficient between the two sets of scores reduced. In validating the instrument, stability on the job was used as the criterion of job success. In a group of 100 individuals who were still on the job a year after their interview the average score was 24.6; in a group of 100 employees who were hired and dismissed within a year the average score was

[25] W. V. Bingham and B. V. Moore, *How to Interview.* Harper, New York, 1941.

[26] C. I. Hovland and E. F. Wonderlic, *J. Applied Psychol.*, *23*, 537 (1939).

21.3. The difference is statistically significant. The dismissed group had a *lower* average score in each of the four subsections. The differences in the category of work history were most marked.

In another group of 300 hired individuals a progressive decrease in the percentage of dismissals with increasing scores was observed (see Fig. 1). The company in which the instrument was developed and validated was a large personal loan organization. The jobs involved to a large degree contacts with the public, a situation in which the use of employment interviews may be particularly fruitful.

Whenever possible, the interview should be supplemented by measurements of the applicant's knowledge of the job, of work proficiency of men with previous specific training, and of work capacities—intellective, sensory, motor, emotional—of men without experience with work for which they are hired.

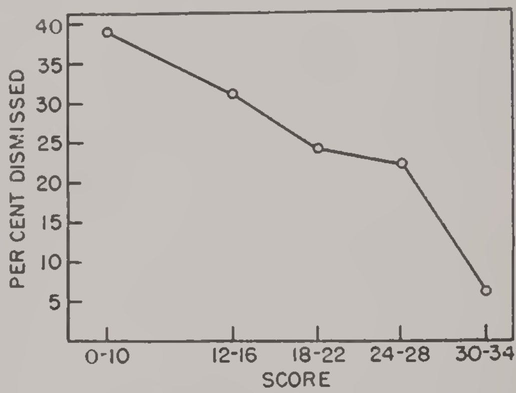


FIG. 1. Scores in a standardized pre-employment interview and the labor turnover.[26] Turnover was expressed as percentage of individuals who were dismissed within a year.

2. Tests

Job knowledge and work proficiency. Among the measures of occupational proficiency of men doing skilled (and some semiskilled) work an important place is occupied by the standardized oral questions determining the applicant's trade knowledge. Most systematic work in this area has been done by the Worker Analysis Section under the Occupational Research Program of the United States Employment Service in their attempts to develop better means for estimating the essential characteristics of job applicants.[27]

Standardized objective tests of work proficiency were developed only for a limited number of jobs, particularly clerical. Such tests, for example, the tests of typing proficiency, can be used not only as an aid for selecting new employees from among a larger number of applicants, but also in the process of training and in the upgrading of the workers who are already on the job and are considered for more responsible typing work.

An attempt to construct a realistic test of typing ability that could be used for the different purposes just mentioned has been made by Jurgensen.[28] The current typing tests, measuring the speed and accuracy of copying a printed text, appeared to fail to predict job success satisfactorily. Reasons for this failure were seen in the fact that the test situation was too abstract and that a number of factors essential in the actual job of typing were omitted, such as following instructions, noting and correcting errors, typing of different kinds of materials, as well as the mechanics of

[27] H. F. Osborne, in *Occupational Counseling Techniques*. American Book, New York 1940.

[28] C. E. Jurgensen, *Educ. Psychol. Measurement*, 2, 409 (1942).

placement of paper, and so forth. It was felt that the test situation should be as comparable as possible to the actual work situation, not only because such a test may be expected to have a higher statistical validity in the sense of differentiating between successful and unsuccessful typists but also because it has a high "apparent validity" both to those tested and to the supervisors. The test consists of four scored parts: (*1*) copying a typewritten rough draft with corrections to be made as indicated; (*2*) tabulating material; (*3*) copying a letter written in longhand ; and (*4*) alphabeting a list of books according to the authors' names, and recording other information such as publication dates. The test differentiated the typists of high caliber, those of low caliber, and those who were released as inadequate. The respective mean scores, combining the length of time of completing the task and the number of errors, were 92 ($N = 28$), 135 ($N = 39$), and 178 ($N = 10$); the lower scores indicate the better performance. The differences between the groups were highly significant. The biserial coefficients expressing the correlation between a test score and the high or low caliber of the typists were $r = 0.796$ for time score, $r = 0.711$ for error score, and $r = 0.957$ for a combined time-error score.

Intelligence and aptitudes. The concept of optimal level of mental capacity and the tests of "general intelligence" are of practical usefulness, even though the range of general-intelligence scores in any occupation is wide.[29]

From the technical point of view, a number of intelligence tests available on the market are satisfactory as psychometric tools. Their usefulness for industrial selection depends on the amount of "mental ability" needed on the job. In routine, repetitive work a high intelligence may actually be a handicap. In addition to the tests for measuring "general" intelligence, one may find good use for those of special aptitudes, such as clerical aptitude or mechanical comprehension. In a study concerned with the effectiveness of tests of general intelligence in predicting job success estimated on the basis of supervisory ratings of 19 radio-tube mounters,[30] low-intelligence scores tended to indicate the poorer workers; average- or above-average-intelligence scores did not differentiate workers rated as "good" and as "fair."

Experimental administration of a battery of psychological tests in a plant manufacturing aircraft engines[31] indicated that job success in simple, purely manual tasks had no relation to scores in the Otis Beta Test of Mental Ability, Bennett Test of Mechanical Comprehension, and Minnesota Paper Form Board (a test of spatial thinking). On the other hand there was a positive and significant relationship between the scores on these tests and success on jobs requiring skill and judgment. The detailed data are given in Table 3.

The test results obtained at the time of applying for the job can be used profitably not only in immediate selection and placement but also in promotions to supervisory and executive positions.

[29] W. V. Bingham, *Aptitudes and Aptitude Testing.* Harper, New York, 1937.

[30] G. Forlano and F. H. Kirkpatrick, *J. Applied Psychol.*, **29**, 257 (1945).

[31] J. T. Shuman, *J. Applied Psychol.*, **29**, 156 (1945).

TABLE 3

Correlations Between Job Ratings and Test Scores[31]

Job group	Test		
	Otis Q.S. Test of Mental Ability	Minnesota Paper Form Board	Bennett Test of Mechanical Comprehension
Inspectors	0.52 ± 0.09	0.50 ± 0.09	0.66 ± 0.13
Engine testers	.57 ± .13	.16 ± .17	.17 ± .17
Machine operators	.48 ± .08	.38 ± .08	.44 ± .08
Foremen	.39 ± .07	.47 ± .07	.46 ± .07
Job setters	.46 ± .14	.59 ± .13	.73 ± .10
Tool room learners	.48 ± .09	.42 ± .09	.46 ± .09
Mean biserial *r*	.49 ± .04	.44 ± .04	.52 ± .03

In validating a selection test we must consider not only the immediate output but also the relationships between the test scores and stability on the job. Relative labor stability is one of the conditions essential to successful plant operation. The problem of rapid labor turnover was particularly critical in the war years, but maintenance of a stable work force is an ever present challenge to the personnel department. A high rate of labor turnover is especially critical when it affects jobs that require a prolonged training. But even in semiskilled jobs the cost of replacing an employee usually amounts to much more than the cost of training one new worker. Thus in the task of selecting workers one must consider both the potential production efficiency and their expected length of service. The investigation of the relationship between various personal characteristics and turnover has to be carried out for different job groups separately. Recently such a study has been made in a newly opened plant employing, at the start, 64 women.[32] The workinvolved the use of power-driven sewing machines. After two months fourteen wo rkers quit voluntarily. Table IV indicates some of the characteristics of the group that stayed on the job and of the group that quit. The workers that quit were, on the average, six years younger, had fewer years of previous employment, and had a higher measured intelligence. In other types of jobs the relationship might be very different.

The relation between the level of general intelligence and labor turnover is not the same from company to company even for occupational groups carrying the same label.[33] In one company employing men clerks a direct positive relationship was found between the scores obtained in a mental alertness test and labor stability: men with low scores were less stable on the job than men with high scores. In another company employing women clerks the relationship was more complex. Again in the group having low test scores the labor turnover was high; it decreased with the higher test scores but rose again for clerks scoring more than 50 points. The

[32] H. Beaumont, *Univ. Kentucky Personnel Bull.*, **2**, No. 1 (1944).
[33] A. W. Kornhauser, *J. Personnel Research* **1**, 103 (1923).

TABLE 4

Some Personal Characteristics and Labor Stability[32]

Characteristic	Group	
	Stayed	Quit
Number of persons	50	14
Average age	29.4	23.4
Years of education	9.3	10.6
Years of previous employment	5.6	2.3
Score on intelligence test	11.8	14.9

general work conditions, wages, specific demands of the job as well as opportunities for promotion might have been among the factors responsible for the differences between the two groups.

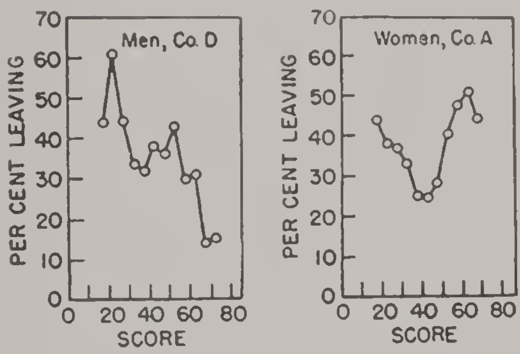


FIG. 2. Labor instability in relation to mental alertness test scores.[33] Each point on the graph represents the percentage of employees making a given test score who had left the company within a period of six months from the time of employment.

Tests of motor capacity. In describing a man's fitness under laboratory conditions we can abstract four broad aspects of voluntary motor performance: strength, speed, co-ordination, and endurance. Using standardized performance tasks we can study the changes in motor fitness due to experimentally induced stresses.[34] When we have to select men for manipulative industrial jobs the situation is much different and much more difficult.

The "psychological" tests of motor capacity are designed to measure fundamental aptitudes for manual occupations.[29] The Minnesota Manual Dexterity Test measures the speed with which the subject picks up, transfers, and places cylindrical blocks in holes in a board; this performance involves gross movements of hand and arm. The test may be modified to serve also as a measure of finger dexterity: in this case the subject is asked to turn over the discs placed in the board. Another test of finger dexterity, devised by Johnson O'Connor, consists in picking up small cylindrical brass pins and placing them in holes in a metal plate. The correlation between the two functions, speed of large movements and skillful finger movements, is low.

[34] H. L. Taylor, J. Brozek, A. Henschel, O. Mickelsen, and A. Keys, *Am. J. Physiol.*, **143**, 148 (1945).

A group of butter wrappers had relatively low scores on O'Connor's finger dexterity test, whereas on the block placing, 92 per cent of the general population had lower scores than the average butter wrapper.

The selection of workers for manual operations on the basis of "abstract" manipulative tests is impeded by the specificity of motor abilities; we do not have a manipulative quotient comparable to an intelligence quotient (I.Q.) that serves to characterize the "general intelligence level." It has been a repeated experience that motor tests are of use chiefly when the tests closely resemble the operation that the worker will actually perform.

The use of motor tests of the "miniature situation" type in the selection of semiskilled workers can be illustrated by the material from the Kearny Works of Western Electric Company.[35] For the selection of coil winders a standardized, *simplified work sample* was developed in which the task consisted of winding wire around screws fastened on a board; time was used as the test score. When a group of 113 workers who were already on the job were tested, it was found that the test discriminated satisfactorily between the more efficient and less efficient employees. Ninety-two per cent of the employees with above-average performance on their jobs had scores on the winding test above the "critical" score, whereas only twenty-eight per cent of the employees with below-average job performance had scores above the critical. In employing only those applicants who are above the critical or passing score, the probability of success on the job is significantly improved.

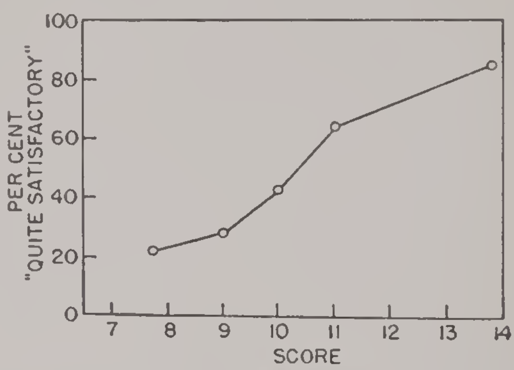


FIG. 3. Relation between near acuity scores and rated performance of 225 radio tube assemblers.[38]

Sensory functions. Of the special senses, vision is by far the most important for industrial performance. The problems of job analysis with reference to the visual characteristics and skills of industrial workers and visual testing in industry have been discussed in detail by Kuhn[36] and by Tiffin.[37] Emphasis has been placed on testing such visual characteristics as acuity of near vision, acuity of distant vision, and depth perception and phorias, and on determining normal requirements for the different jobs as a basis for selective placement. A positive relationship may be expected between acuity of near vision and performance on jobs requiring manipulation of small parts. Figure 3 shows the actual existence of this relationship for a group of 225 radio-tube assemblers. The acuity of near vision was measured as the ability to see progressively smaller details at a distance of thirteen inches from the eyes;

[35] D. W. Cook, in *Psychological Aids in the Selection of Workers.* American Management Assn., New York, 1941.

[36] H. S. Kuhn, *Industrial Ophthalmology.* Mosby, St. Louis, 1944.

[37] J. Tiffin, *Industrial Psychology.* 2nd ed., Prentice-Hall, New York, 1947.

a higher score represents a better performance. The job performance was rated by the plant supervisors as either "quite satisfactory" or "not entirely satisfactory." In the total group 53 per cent were rated in the first category. The percentages varied for different score levels of the near acuity test; the better the near acuity score, the greater the percentage of "quite satisfactory" workers.[38]

Personality. The term "personality," in the inclusive sense, refers to the whole of the affective, conative, intellective, sensory, and physical characteristics of an individual. In this context we shall use the term to denote those aspects of total behavior that refer to personal and social adjustment.

In some jobs the personality characteristics carry considerably greater weight than the abilities.[39] This situation might be illustrated by comparing the relationship between general intelligence and introversion-extroversion on one hand and successful salesmanship on the other (Table 5). The general intelligence was measured by Otis's self-administering test of mental ability and the personality type was evaluated on the basis of a psychiatric interview. The two groups of salesmen that are contrasted represent 25 per cent of the salesmen on the "low" and the "high" end of the distribution according to their "cost of selling," determined from the relation of wages to sales. The total sample consisted of 284 sales clerks. There are only slight differences in percentages of low- and high-cost salesmen at different levels of intelligence. The "personality types" differ strikingly: the extroverted individuals are, on the whole, much more successful than those classified as introverted.

TABLE 5

Intelligence and the Personality Types of More Successful and of Less Successful Sales Clerks[39]

Type	Group	
	More successful	Less successful
Intelligence		
Superior (I.Q. above 110)	5.6	4.2
Average (90–109)	46.4	36.6
Dull average (80–89)	33.8	36.7
Subnormal (70–79)	11.3	19.6
Borderline mental defect (60–69)	2.9	2.9
Total	100%	100%
Personality		
Extrovert	54	11
Ambivert	36	49
Introvert	10	40
Total	100%	100%

In industry the personality factors affect deeply both individual efficiency,

[39] J. Tiffin and S. E. Wirt, *J. Consult. Psychol.*, 8, 80 (1944).
V. V. Anderson, *Psychiatry in Industry*. Harper, New York, 1929.

interpersonal relations of the workers, and the relations between labor and management. Yet the psychometric techniques in this area are not satisfactory. There are numerous instruments, tests, and questionnaires that were found useful in guidance and clinical situations[40, 41] and the amount of experimental work is considerable[42] but the usefulness of these devices for industrial selection and placement is very limited. Valid use of adjustment questionnaires, psychoneurotic inventories, measures of opinions and interests, and other devices that depend on the applicant's self-description presupposes an attitude of truthfulness and disinterestedness that cannot be postulated in employment-application situations. It has been pointed out that it is possible by instructing subjects taking Bernreuter's Personality Inventory (neurotic tendency, self-sufficiency, introversion-extroversion, dominance-submission, confidence, and sociability) to change significantly the responses and "improve" the scores.[43]

TABLE 6

Correlation Between Scores Obtained in "Clinical" and "Employment" Situations on the Humm-Wadsworth Temperament Scale for 65 College Students[37]

Temperamental component	Coefficient of correlation
"Normal" (self-control)	−0.03
Hysteroid	+0.42
Manic	+0.09
Depressive	−0.10
Autistic	+0.11
Paranoid	+0.61
Epileptoid	+0.23

The Humm-Wadsworth Temperament Scale was specifically devised for use in industrial personnel work and can be considered as a "partially disguised" personality test. Yet when a group of 65 college students took the scale first in a frank (or "clinical") situation and then changed to a job-application situation, the correlation between the two sets of scores for the seven temperament components was low (Table 6).

The projective techniques, especially the Rorschach Test, in which it is much less likely that the subject can guess what is a "good" and a "bad" response, are used widely in psychiatric clinical and research work. The development of methods for group administration[44] increases the possibility of using the Rorschach Test for industrial purposes, but the practical value for industrial selection remains to be

[40] P. M. Symonds, *Diagnosing Personality and Conduct*. Century, New York, 1931.

[41] D. C. Paterson, G. G. Schneidler, and E. G. Williamson, *Student Guidance Techniques*. McGraw-Hill, New York, 1938.

[42] J. B. Maller, in *Personality and Behavior Disorders*. Ronald, New York, 1944.

[43] A. E. Traxler, *The Use of Tests and Rating Devices in the Appraisal of Personality*. Educational Records Bureau, 1942.

[44] M. R. Harrower-Erickson and M. E. Steiner, *Large-Scale Rorschach Technique*. Thomas, Springfield, Ill., 1944.

demonstrated. Some encouraging results have already been obtained. Thus, four characteristics of the responses on group-Rorschach were found useful in discriminating between outstanding and mediocre young male mechanical workers.[45]

C. LIMITATIONS—PHYSICAL HANDICAPS

The problems of specific work disabilities and their evaluation were summarized[46] in a handbook that grew out of a decade of experience of the United States Employment Service. The material covers the defects of speech and hearing, orthopedic, respiratory, cardiovascular, and miscellaneous physical handicaps, visual defects, neurological disorders, and mental limitations. The handicaps are evaluated with reference to their effect on work capacity and the limitations they place upon suitable working conditions.

The underlying philosophy of the handbook is a healthy one. The number of men and women who are completely unemployable is small. The majority of the handicapped are limited only in some aspects of work capacity, and if their *assets* as well as their liabilities are considered in selective placement they can become productive members of society.

The weaknesses of the technique are again in the diagnosis of the handicap. Translation even of good clinical data obtained in *rest* is fraught with difficulties in predicting the capacities for physical *work*. In the placement of cardiac patients, the history of previous work and other physical activities is helpful, but in the cases of acute illness this information is not available at the time of the release from the hospital.

The effect of clinically diagnosed physical work limitations should be determined in systematic follow-up studies. An opinion was expressed that "possibly only a statistical analysis of what happens to selectively placed workers after three, six, twelve or twenty-four months will serve our translation of clinical criteria into physical capacities analysis."[47]

With heart diseases it is considered essential for the progress of medical occupational guidance to obtain functional and therapeutic classification of the patient, to collect information about the physical factors involved in the job (number of work hours, types and intensity of physical work, traveling time from home to work) and to follow the status of the patient's health while on the job.[48] The therapeutic classification used contains four categories:

Class A — physical activity need not be restricted.
Class B — no unusually severe or competitive efforts permissible.
Class C — ordinary physical activity moderately restricted.
Class D — ordinary physical activity markedly restricted.

[45] Z. Piotrowski, B. Candee, B. Balinsky, S. Holtzberg, and B. Arnold, *J. Psychol.*, **18**, 131 (1944).

[46] *Selective Placement for the Handicapped.* War Manpower Commission, Washington, D. C., 1943.

[47] C. Kuh and B. Hanman, *J. Am. Med. Assoc.* **125**, 265 (1944).

[48] B. Kresky and L. J. Goldwater, *Am. Heart J.*, **27**, 623 (1944).

It is disturbing to note that 43 per cent of the patients of the class B and 50 per cent of the class C were employed as waiters and waitresses or were doing unskilled manual labor. It is true that, "An estimate of how much work a patient *should* do is of little value unless the patient can be provided with a job that does not require more work than is considered advisable."[48] On the other hand, the value of the therapeutic classification can be demonstrated only if we know in detail how it predicts what the worker *can* do and what the consequences are to the worker of not being able or willing to follow the advice of the clinic.

A comprehensive study of job performance of physically impaired workers was conducted by the Medical Division of the United States Civil Service Commission.[49] A sample of nearly 3000 physically impaired male and female workers was compared with over 5000 able-bodied men and women of similar occupation, age, and length of experience on the job. In placing the physically handicapped, account had been taken of their physical capacities as well as their educational and vocational training.

TABLE 7

Percentage Distribution of 2380 Male and 478 Female Physically Impaired Workers by Type of Disability[49]

Type of physical disability	Male	Female	Type of physical disability	Male	Female
Amputation of			Disability or deformity of (*Continued*)		
Arm	5.4	2.3	Back or spine	5.2	5.9
Hand	1.7	0.6	Hips or shoulders	0.4	0.9
Fingers	5.2	3.2	Vision defects		
Leg	7.4	2.9	Blind	1.7	3.6
Legs	0.5	....	Blind in one eye, sound vision in other	18.5	13.8
Foot	1.0	0.2	Other defects		
Feet	..	....	Deaf	2.3	6.9
Disability or deformity of			Hard of hearing	5.3	5.5
Hip or shoulder	2.8	4.2	Cardiac	7.7	10.9
Arm	5.9	5.0	Dwarf	0.3	0.4
Arms	0.6	0.2	Diabetes	0.1	....
Hand	1.6	2.3	Epilepsy	0.1	....
Hands	0.2	0.8	Tuberculosis (pulmonary, arrested)	5.4	5.2
Fingers	0.4	0.8	Pulmonary disease other than tuberculosis	0.6	....
Leg	13.6	18.2			
Legs	3.0	2.9			
Foot	2.4	2.7			
Feet	0.7	0.6			

Both groups were employed in such industrial establishments as aircraft factories, ordnance plants, shipbuilding, and administrative offices. The percentages of different occupational groups composing the sample of the physically impaired workers were as follows: craftsmen, 28.2 per cent; operatives, 18.7 per cent; laborers, 26.1 per cent; service, 3.6 per cent; clerical, 21.3 per cent; professional and semi-professional, administrative, technical and scientific workers, 2.1 per cent. The percentage distribution of the physically impaired by sex and type of disability is given in Table 7.

[49] V. K. Harvey and E. P. Luongo, *J. Am. Med. Assoc.* **127**, 902, 961 (1945).

Productivity, accident rate, sickness absenteeism, and rate of turnover were used as the main criteria of job adjustment. Estimates of quantity and quality of production were furnished by foremen and supervisors. On the basis of these estimates as well as over-all efficiency ratings the percentages of workers rated as producing much more and somewhat more than other workers (quantity), doing much better and a somewhat better job (quality), and getting efficiency ratings of "excellent" and "very good" were slightly but consistently higher for the able-bodied than for the impaired workers (Table 8).

TABLE 8

Percentage Distribution of Physically Impaired and Able-Bodied Workers by Quantity and Quality of Production and Over-All Efficiency on the Job (N = 2858 and 5375, Respectively)[49]

Work	Physically impaired	Able-bodied
Quantity		
Much more than other workers	5.9	6.9
Somewhat more than other workers	21.5	24.6
About the same as other workers	56.3	58.3
Somewhat less than other workers	13.9	8.4
Much less than other workers	2.4	1.8
Quality		
Much better job than other workers	6.6	8.3
Somewhat better job than other workers	23.7	23.8
About the same as other workers	63.2	63.4
Somewhat worse job than other workers	5.9	4.0
Much worse job than other workers	0.6	0.5
Efficiency rating		
Excellent	8.6	10.2
Very good	34.3	35.2
Good	43.6	43.5
Fair	10.8	9.3
Unsatisfactory	2.7	1.8

In terms of accident rates, the average *frequency* rate, expressed as the number of lost-time accidents per million man-hours exposure, was higher for the physically impaired workers than for the able-bodied; the figures were 16.15 and 12.26 respectively. There was no significant difference in the average *severity* rate of the accidents, expressed as the time (in days) lost per 1000 hours worked; the rate was 0.21 for the physically impaired and 0.20 for the able-bodied. The largest difference in the lost-time accident experience of the impaired and able-bodied was among the craftsmen and the operatives. The accident rates for workers with different types of physical impairment are given in Table 9. The rates were strikingly high in workers with hearing defects. The data concerning the differential accident rates for various types of defects should be carefully considered by safety engineers. With respect to sickness absenteeism, the physically impaired workers had a slightly higher absenteeism rate as compared with their controls. The number of days lost annually per worker through sickness was 7.7 and 9.6 for impaired men and women, respectively:

7.0 and 8.7 for able-bodied men and women, respectively. On the other hand, the turnover among the impaired workers (5.4 per cent) was much lower than among able-bodied (52.9 per cent), even after the number of job separations due to the draft were subtracted from the total number of separations.

TABLE 9

Frequency and Severity of Accidents for Persons With Different Types of Physical Impairment[49]

Type of disability	Frequency rate	Severity rate
Total	16.15	0.21
Amputation of		
Arm or arms	14.82	0.05
Fingers	21.10	0.51
Leg or legs	13.00	0.17
Disability or deformity of		
Shoulder or hip	30.01	0.22
Spine or back	10.20	0.15
Upper extremities	16.34	0.20
Lower extremities	11.08	0.23
Other defects		
Visual defects	15.86	0.15
Hearing	36.36	0.47
Cardiac	13.07	0.21
Tuberculosis	11.60	0.08
Other	17.23	0.02

D. LIMITATIONS—OLD AGE

In view of the steadily increasing relative number of older people, it is economically imperative, as well as desirable for humanitarian reasons, to keep their experience and skills in the productive service of society. The shifts in population structure proceeded very rapidly within the last one hundred years with the average age of the population shifting continuously toward higher values. Stieglitz reports that in 1900 only 17 per cent of the total population of the United States exceeded 45 years of age; in 1940, this age group comprised 26.5 per cent of the population.[50] This trend is still present and has to be considered by all concerned with industry as an integral part of the socioeconomic structure of our society. The war pushed aside the problem of employment for the older worker but has not solved it.

In the selection of young employees the personnel man is concerned only with the immediate capacities of the applicant; in employing older people the possible decrease in physical fitness with age must be considered. Prediction of this trend in individual cases is as yet impossible. It is only on the basis of thorough periodic examinations, together with consideration of the actual production records, that intelligent and timely job reassignments within the industry can be carried out. The need for retraining of the aging employees suited to their capacities as wellas to their limitations has been emphasized.[51]

[50] E. J. Stieglitz, ed., *Geriatric Medicine*. Saunders, Philadelphia, 1943, p. 13.
[51] E. J. Stieglitz, *J. Am. Med. Assoc.* **116**, 1383 (1941).

The presence of a decrease in the efficiency of bodily functions in the process of normal aging is well established.[52] There is decreased speed, strength, and co-ordination of skeletal neuromuscular reactions as well as impairment of sensory and mental functions.[53-55] In moderately hard physical work—treadmill walking for 15 minutes at 5.6 km. per hour on a grade of 8.6 per cent—the mechanical efficiency, expressed as the ratio of energy output (work performed) to energy input (calculated from the O_2 intake), does not show a decrease in older people.[56] Except for the oldest group (mean age 75 years), the subjects achieved and maintained a "steady state." In severe work one of the important physiological factors limiting performance is the capacity to supply adequate amounts of oxygen to the tissues. This capacity decreases markedly with age (Table 10).

TABLE 10

Age and Maximal Oxygen Intake[56]

Mean age, years	Number of subjects	Mean maximal O_2 intake, l./min.	O_2, cc./kg. body wt. per min.
17.4	11	3.61	52.8
24.5	11	3.53	48.7
35.1	10	3.42	43.1
44.3	9	2.92	39.5
51.0	7	2.63	38.4
63.1	8	2.35	34.5
75.0	3	1.71	25.5

In a number of psychological functions the decline in fitness is already evident in the thirties, becomes marked in the fifties, and striking in the seventies. When the flicker fusion frequency, an index of the efficiency of the light-registering apparatus, was determined in a group of women the average scores were 46.7 flickers per second for the age group 18 to 25 years, 45.7 for age group 26 to 35, 45.4 for age group 36 to 45, and 40.9 for age group 46 to 60.[57]

When Miles[58] measured the speed of performance of different age groups in a simple manual task, the scores representing the time required for completion of a short series of movements showed only slight changes in the range of 20 to 50 years in men and 20 to 45 years in women. There was a marked and progressive deterioration of performance in the higher age groups (Table 11). In general, the changes in women take place sooner and are slightly more marked.

[52] A. J. Carlson, in E. J. Stieglitz *Geriatric Medicine*. Saunders, Philadelphia, 1943, p. 51.

[53] W. R. Miles and C. C. Miles, in E. J. Stieglitz *Geriatric Medicine*. Saunders, Philadelphia, 1943, p. 99.

[54] J. A. Babbitt, in E. J. Stieglitz *Geriatric Medicine*. Saunders, Philadelphia, 1943, p. 303.

[55] B. Rones, in E. J. Stieglitz *Geriatric Medicine*. Saunders, Philadelphia, 1943, p. 294.

[56] S. Robinson, *Arbeitsphysiol.*, **10**, 251 (1939).

[57] J. Brozek and A. Keys, *J. Consult. Psychol.*, **9**, 87 (1945).

[58] W. R. Miles, *U.S. Pub. Health Repts. Supplement* No. **168**, 34 (1943).

TABLE 11

Age Changes of Dexterity (after Miles)

Age group	Scores[a] Men	Scores[a] Women	Age group	Scores[a] Men	Scores[a] Women
20–24	111 (23)	112 (21)	55–59	124 (33)	132 (53)
25–29	112 (19)	110 (17)	60–64	135 (26)	139 (60)
30–34	114 (20)	114 (28)	65–69	141 (27)	144 (54)
35–39	116 (20)	113 (22)	70–74	139 (27)	164 (41)
40–44	115 (21)	112 (27)	75–79	158 (15)	154 (23)
45–49	112 (18)	124 (30)	80–84	185 (11)	181 (14)
50–54	117 (25)	127 (51)			

[a] The scores, in 1/100 sec., refer to the performance by the dominant hand in a reaching-and-placing test.
The number of subjects in each group is indicated in parentheses.

Manual performance of men of different age groups has been studied under laboratory conditions by Smith.[59] In the short, 15-minute work period the average number of assembled nut-and-bolt units for the age groups 30, 40, and 50—expressed as percentage of age group 30—was 100.0 per cent, 95.7 per cent, and 91.9 per cent respectively.

The long assembly period in Smith's investigations consisted of 4 hours of uninterrupted work. In this performance task, which resembled more closely an actual industrial situation, the age decrement in the ability to perform a high-speed manual work was still more marked. The respective percentages were 100.0 for the 30-year group ($N = 39$), 93.6 for the 40-year group ($N = 41$), and 86.5 for the 50-year group ($N = 34$). The difference between the "30" and "50" group is statistically highly significant, $C.R. = 4.48$. However, it should be noted that 34 per cent of the 40-year-olds and 15 per cent of the 50-year-olds reached or exceeded the median of the 30-year group. This fact is important for the placement of older workers and re-emphasizes the principle that individual differences should be taken into account in all phases of personnel work. It is interesting that the process of "warming up" and the fatigue decrements were not different in the age groups studied (Fig. 4).

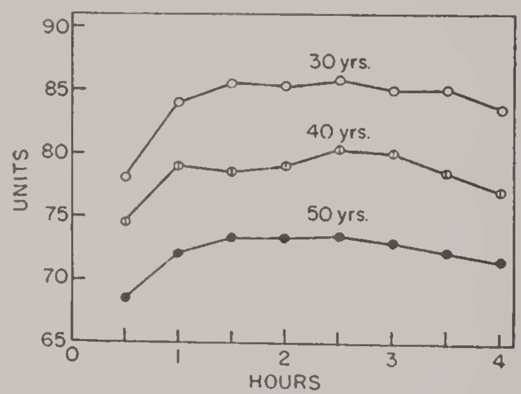


FIG. 4. Age and work curves.[59] Average production on nut-and-bolt assembly for the age groups 30, 40, and 50. Work done in the laboratory.

In a population of adults from 20 to 90 years of age, manual dexterity was measured by the Link McFarlane Cube Assembly test; there was a gradual decline to the 60's and a larger decrease from then on.[53] This trend was characteristic for

[59] K. R. Smith, *J. Applied Psychol.*, **22**, 295 (1938).

the population as a whole. However, older men who had mechanical training maintained the speed rate of young adults into late maturity. The fact that experience and practice can diminish or even counteract the age decrement of manual abilities is of great significance. For another test used by Miles, the McFarlane Coat Assembly Test, the women had more training than men. It was not surprising that they had better scores at all ages. At the same time the speed decrement with age was strikingly slower. Men showed a definite decrease from decade to decade with a lengthening of work time from a score of 570 in the 30's to about 800 in the 60's; the comparable scores for women were approximately 350 and 450, respectively. This again demonstrates that experience can act as a delaying factor in the decline of a manual skill.

Research on adult mental abilities indicates that not all intellective functions follow the same course of decline with age. These differential trends are again explained in terms of practice, of use and disuse. Abilities that are part of adult experience, such as maintenance of a large vocabulary, do not decline with adult age and may even increase. In performing tasks that are remote, such as thinking in terms of geometrical symbols, there is an age decrement.[60] It should be strongly emphasized that within every age group there is a wide range of mental, motor, intellective, and personality characteristics. Age alone can rarely, if ever, serve as a criterion for predicting the performance capacity.

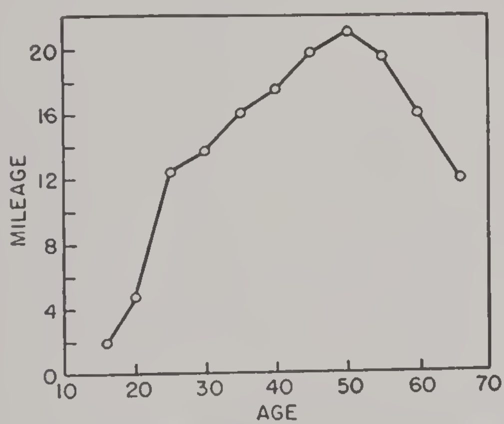


Fig. 5. Mileage, in millions of miles driven per fatality, for drivers of different ages.[61]

There is a great need for further data on the relationship between age and industrial work capacity. The information obtained in experimental laboratory studies provides only very indirect clues as a basis for practical decisions. There is a lack of information on actual *industrial productivity* of men and women of different age groups. This information can be obtained only by pooling the data collected for comparable industrial operations in a number of plants.

The quantity and quality of industrial output are not too closely related to the capacity for maximum performance. As a result of psychological factors, actual performance can improve even when the physiological functions undergo deteriorative changes. Such behavioral characteristics as "carefulness" can change profoundly the picture predicted on the basis of the physiological factors alone. Although glare vision, steering (eye-hand) coordination, and braking reaction—three physiologically important components of driving "fitness"—show a steady deterioration with age starting in the 30's, the

[60] H. Sorenson, *Adult Abilities.* Univ. Minnesota Press, Minneapolis, 1938.

safety of driving measured in terms of millions of miles per fatality increases up to 50 years of age; it declines rapidly in the next two decades.[61]

III. Problems of Fatigue

The problems of industrial fatigue and its reduction are virtually identical with the whole field of industrial management and personnel work. One of the aims of scientific placement, of matching men and jobs, is to reduce the strain put on the worker when there is only a small "margin of safety" between his capacities and the requirements of the work done. Also, the physical environmental factors—illumination, noise, temperature, humidity, and rate of movement of the air—have bearings on fatigue. On the other hand, the tensions in the social environment may be more of a "strain" than long hours of hard physical work.

Thus the consideration of personal factors in industrial fatigue covers a series of interacting phenomena ranging from the physiological through psychological to the sociological level. The appraisal of the single factors should be made within the large, multivariable context.

The interest in the "total situation" has been stressed by the National Research Council Committee on Work in Industry. It is unfortunate that in the actual treatment of the subject of the fatigue of workers[62] no effort has been made to approach the subject systematically and to present evidence concerning to what degree and under what conditions the various physiological, psychological, and sociological components in the industrial situation act as factors limiting human performance capacity, actual industrial output, or both.

A. APPROACH TO THE STUDY OF FATIGUE

Methodologically, industrial fatigue can be studied by means of subjective reports, measured functional changes, and industrial output records.

1. Subjective Reports

The changes in the feeling of well-being are prominent in the popular concept of "fatigue" and on the basis of the subjective sensations different types of fatigue can be distinguished. Fatigue resulting from hard muscular work, accompanied with the sensation of strain, and relieved only by rest, differs from fatigue accompanying light, repetitive, "monotonous" work, or weariness-fatigue related to physical illness, anxiety states, intense mental work, or lack of sleep. Yet introspective self-observation is mistrusted as a scientific tool. One can distinguish only gross degrees of departure from "normal" and even then it is difficult, if not impossible, to achieve an intersubject uniformity in judging the severity of the various subjective symptoms of fatigue.

[61] H. R. De Silva, *Sci. Monthly*, **47**, 536 (1938).

[62] N.R.C. Committee on Work in Industry, *Fatigue of Workers*. Reinhold, New York, 1941.

2. Measured Functional Changes

Another approach to the study of industrial fatigue consists in determining the effects of work on the functional state of the human organism. Hard physical work produces striking changes in a number of physiological and biochemical characteristics.[63] These methods are valuable in laboratory studies on "physical fitness," but their usefulness for industrial fatigue research is limited. Only under conditions of hard physical work and of extreme environmental strain, especially heat, will they provide useful information. Most of the modern industrial jobs involve light to moderate muscular work, which is physiologically defined as work yielding a mean metabolic rate of less than three times the basal metabolic rate.[64] The slight over-all increase in metabolism is apt to mask the fact that the activity of small muscle groups involved in rapid, repetitive movements characteristic of many industrial operations may be extremely intense. This strain on the neuromuscular mechanisms is not adequately reflected in the changes registered by the cardiorespiratory system or metabolism.

The physiological adjustments of the working organism are slight and the classical methods of work physiology—such as determination of oxygen consumption, heart rate and blood pressure, measurement of body temperature, and analysis of changes in blood composition—are not sensitive enough for the study of typical industrial work fatigue although they characterize, in objective and quantitative terms, the state of a man doing heavy muscular work.

Vision plays an important role in many industrial operations and visual discomfort and fatigue are frequent complaints. However, the development of criteria of ocular fatigue in terms of functional changes has not been satisfactory. It has been observed that work at visual tasks is followed by such phenomena as decrease in the speed with which the eyes accommodate from near-vision to distant-vision and decrement in visual acuity, but the changes are small even in prolonged, intensive visual work. Various psychophysiological effects of seeing were studied in relation to differences in illumination, such as changes in "nervous muscular tension" measured as pressure unconsciously exerted by fingers resting on a key, rate of blinking, and size of the pupil,[65] but their usefulness for research on industrial fatigue is limited. For some time it appeared that one visual function, the fusion frequency of flicker, might be used as a physiological avenue to the central nervous system and thus reflect the central component of fatigue.[66] Evidence obtained in this laboratory indicates that the flicker fusion frequency cannot be considered a sensitive test of "general fatigue" resulting from hard physical work, even when carried on under unfavorable environmental (heat) and nutritional (fasting) conditions.[67] Lack of interlaboratory standardization of the instruments with

[63] E. C. Schneider, *Physiology of Muscular Activity*. Saunders, Philadelphia, 1939.
[64] A. C. Ivy, *J. Am. Med. Assoc.*, **118**, 569 (1942).
[65] M. Luckiesh and F. M. Moss, *The Science of Seeing*. Van Nostrand, New York, 1937.
[66] E. Simonson and N. Enzer, *J. Ind. Hyg. Toxicol.*, **23**, 83 (1941).
[67] J. Brozek and A. Keys, *J. Ind. Hyg. Toxicol.*, **26**, 169 (1944).

respect to the illumination intensity of the test patch and the ratio of light to dark phases may be in part responsible for the contradictory results.

In studying the effects on flicker fusion frequency of work involving visual strain we tested two groups of subjects: one group was doing clerical work in the library of the University of Minnesota, the other group was engaged in routine microscopic work in the laboratories of the Minnesota State Department of Public Health. The measurements were done in the first and last half hour of two successive work days. In both groups on both days the afternoon values were, on the average, lower. However, the average differences were extremely small and statistically not significant.

In an extensive investigation of the fatigue of truck drivers[68] the concept of fatigue was broadly defined as "alterations in psychophysiological state produced by work." The various functional characteristics were studied under conditions of rest (before driving) and after driving. The tests included biochemical and cytological analyses of blood; response to standard hard physical work on the treadmill measured in terms of changes in pulse rate, blood pressure, and respiratory exchange; tests of voluntary motor performance; and visual tests. The symptom-complex of driving fatigue included marked changes in a number of performance tests, especially reduction in speed of tapping and of co-ordinated movements, increase in body sway, and decreased steadiness of the hands. Changes in visual functions including fusion frequency of flicker, were small. The physiological characteristics changed only negligibly and the biochemical findings were negative. The technique of multiple tests represents the safest approach to the study of the effects of work on functional efficiency of the human organism. Studies of the *basic types* of occupational work should decrease the area of uncertainty, establish the sensitivity of different functions to such a "stress," and delimit more sharply the fruitful field and methods for the study of industrial fatigue.

3. *Industrial Output Records*

From the practical point of view the changes in the actual output curves have a strong appeal. The work output is a resultant of capacity plus motivation, and the decrement in output can be interpreted as a decremant of "capacity" only when motivation is being kept constant. For this reason in the laboratory studies of "physical fitness" the performance tests are made under conditions allowing *maximal* performance: the tests are short and the subjects, who are nearly always volunteers, are trained to perform close to the limit of their capacity. Output in this type of work may show a pronounced fatigue decrement or even a complete exhaustion within a matter of minutes. The intensity of industrial work is always submaximal; the wider the gap between the maximum possible output and the actual work intensity, the more important is the influence of the psychological factors lumped together under the label "motivation."

[68] *U.S. Pub. Health Service Bull.* No. 265 (1941).

The changes in motivation as far as they result from work are a legitimate component of industrial fatigue. It is only the external social factors, such as a pressure for a "slow-down," that make a legitimate use of production curves impossible. It appears that fundamental research on industrial fatigue should be carried out in miniature industrial plants combining the realism of actual working conditions with the objectivity and detachment of the laboratory.

B. TYPES OF FATIGUE

On the basis of performance records one can distinguish three types of work fatigue: "exhaustion-fatigue," "tiredness-fatigue," and "boredom-fatigue." The first type of fatigue is almost completely a product and object of laboratory studies; only under pathological conditions, such as telegraphists' cramp, does work production drop to zero. Tiredness-fatigue results from moderately hard to hard work. Boredom-fatigue is an important industrial problem, its importance increasing parallelly to the increase in the number of jobs involving light, repetitive work.

1. *Exhaustion-fatigue*

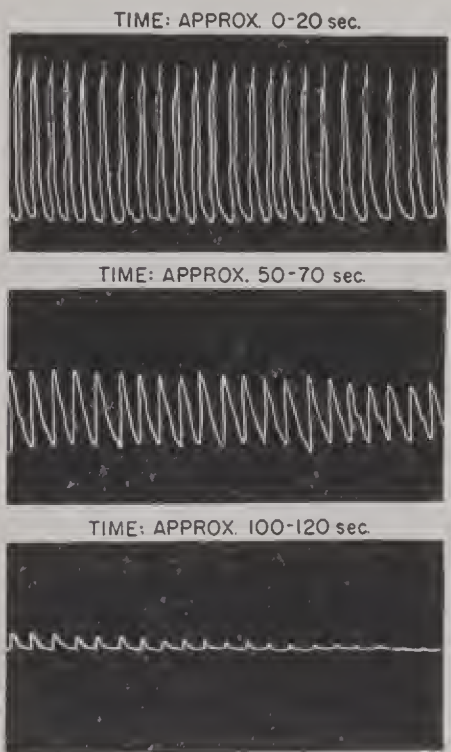


Fig. 6. Exhaustion-fatigue of an isolated muscle (frog gastrocnemius) electrically stimulated at approximately 1-second intervals. Weight lifted was equal to 100 grams. Magnification ratio (fulcrum to writing point : fulcrum to muscle hook) = 16.4/1.8 = 9.1.

The term "fatigue" in the strict but limited sense of "muscular fatigue" is defined as a decrease and finally a temporary loss in irritability and contractility of a muscle, brought on by its continued activity. In its purest form the exhaustion-fatigue can be demonstrated in an isolated muscle attached to a balance beam, with the "work" consisting of lifting a weight attached to the other end of the balance arm. In Figure 6 we observe a progressive decrease in response, recorded as the height to which the weight was lifted, in the face of standard, repeated stimulation applied directly to the muscle. The contractions of the muscle exposed to electrical stimuli of equal strength and following each other at equal, short intervals diminish steadily in height until finally the muscle does not contract at all even though the stimulation is continued.

In human experiments in the laboratory we find essentially similar work curves when a man lifts a weight by flexing his index finger; with suitable load after 30 to 50 lifts no movement of the finger can be produced voluntarily. Another kind of exhaustion-fatigue

is produced in the laboratory when a man runs on the treadmill until he can no longer continue.

Although the physiological mechanisms involved in the three examples of exhaustion-fatigue are very different they are all characterized by a cessation of the work activity.

2. Tiredness-fatigue

In output records obtained in physically "fatiguing" work we usually observe an initial rise, referred to as the "warm-up" effect, followed by progressive decrease in output. In contradistinction to exhaustion-fatigue the terminal performance is far above zero. This type of fatigue is illustrated in Figure 7. The subjects were performing moderately hard work by walking on a motor-driven treadmill at the speed of 3.5 miles per hour and at 5 per cent grade. At half-hour intervals a 5-minute test of manual speed and co-ordination[69] was inserted. The score represents the total number of times a ball-bearing was passed through a vertically held, 1-foot-long conduit pipe. The work curves are typical examples of tiredness-fatigue. The final scores are 4 per cent and 13 per cent, respectively, below the maximal score.

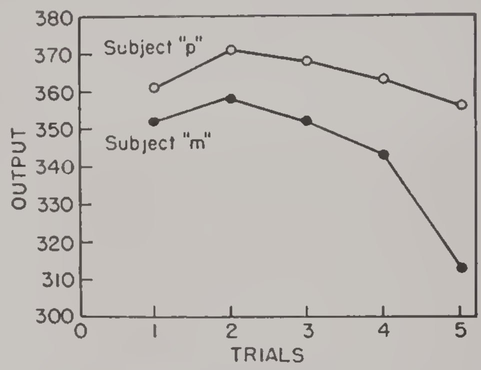


Fig. 7. Tiredness-fatigue in man, laboratory data. Performance in a test of manual speed and coordination, performed at half-hour intervals while walking on treadmill.

Similar output curves were obtainedin medium-heavy and heavy industrial worl.[70] The output (Figs. 8 and 9) is expressed in terms of percentage of maximum production attainable if all workers would reach the highest daily output at the same hour. In the medium-heavy muscular work involved in the operation of "radiator solder" the morning output increases up to the third hour and

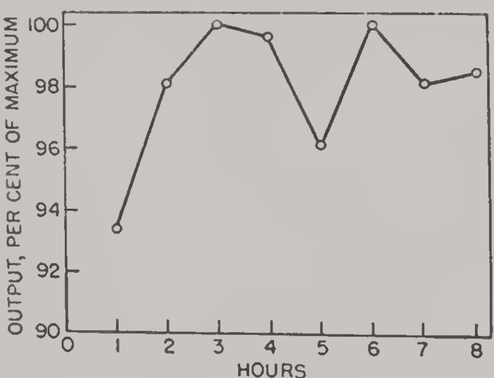


Fig. 8. Tiredness-fatigue.[70] Output in medium-heavy industrial work—radiator solder—during an eight-hour day.

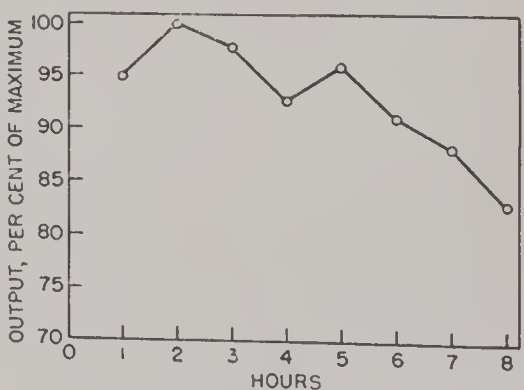


Fig. 9. Tiredness-fatigue.[70] Output in heavy industrial work—ramming molds—during an eight-hour day.

[69] J. Brozek, *J. Gen. Psychol.*, **31**, 125 (1944).
[70] *U.S. Pub. Health Service Bull.* No. **106** (1920).

shows a slight drop in the fourth hour; the afternoon curve follows a similar pattern, except that it starts higher and drops at the end of the work to a slightly lower level. The other type of work consists of packing damp sand about a pattern and involves considerable physical exertion. The maximum hourly output is reached earlier, and the fatigue decrement is of larger magnitude than in the soldering operation. Also, the decrement is progressive and the afternoon curve does not resemble the morning output record.

3. Boredom-fatigue

In light, repetitive work we frequently find output curves characterized by a dip in the *middle* of the working period (see Fig. 10). It is evident that this work decrement cannot reflect a decrease in the physiological work capacity; after the mid-point slump the production curve goes up without "refueling" or a rest-pause recovery. The causative factor is of a psychological, emotional nature.

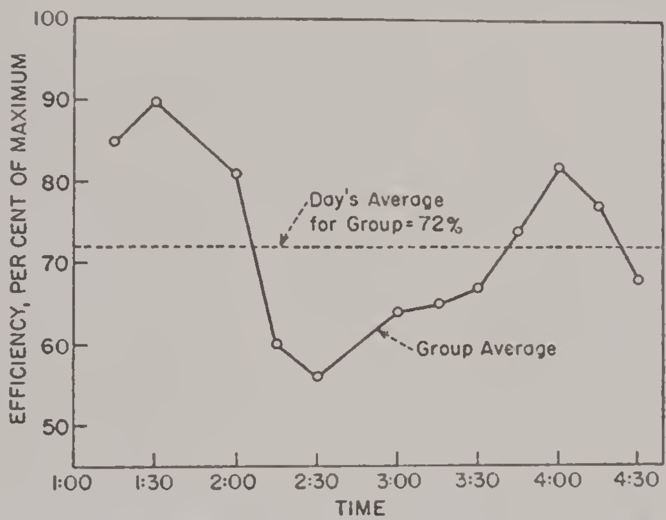


FIG. 10. Boredom-fatigue.[71] An output curve for light industrial work during a P.M. work-spell.

C. REDUCTION OF FATIGUE

In reducing industrial fatigue much attention has been given to environmental factors, such as lighting, partly because they are relatively easy to modify. These factors influence the output both directly and indirectly. Work with significant visual components is more difficult, more fatiguing under conditions of poor illumination. On the other hand, inadequate lighting may produce an unpleasant emotional reaction in the worker and affect his general attitude toward the job. The physical environmental factors must, therefore, be taken into account.

[71] R. L. Cardinell, *J. Acoustical Soc. of America*, **15**, 133 (1943).

1. *Occupational Fitness*

The selection and placement of workers in jobs for which they are fit because of their capacities and training leads to a higher general level of output; it is also important for reduction of fatigue. If two men, with carrying capacity of 150 lb. and 100 lb., respectively, are doing work involving the carrying of 75-lb. sacks, it will obviously be much less fatiguing for the first man than for the second man. Such a prediction has been confirmed experimentally in studying the changes in measured strength at the end of the day's work. The object of the study was the operation of "ramming molds" representing heavy foundry work. Although in the stronger men the average impairment of strength was only 4 per cent, for the weaker men the strength scores decreased by 12 per cent.[70]

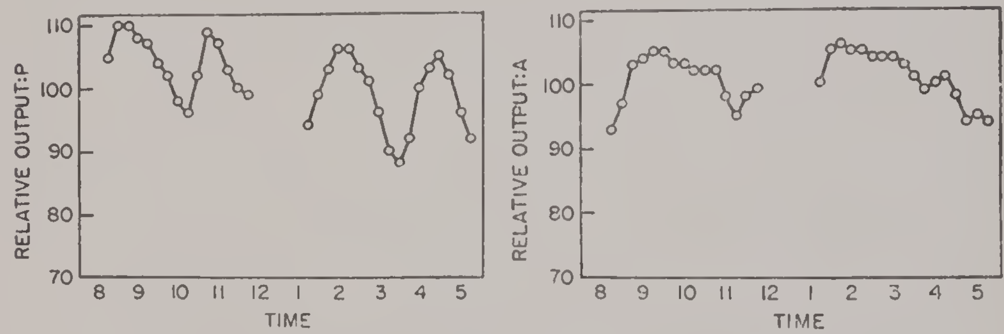


FIG. 11. Output curves of a worker experiencing boredom (P) and free from boredom (A).[72]

The feeling of monotony and the boredom-fatigue are only in part functions of the type of work performed. They depend, also, on the psychological make-up of the individual worker.[72] Thus some workers may exhibit boredom output curves while others working on the same job do not show the typical midperiod slump (Fig. 11). In light, repetitive work the individuals who have higher intelligence and who are more extroverted tend to be more susceptible to boredom-fatigue (Table 12).

TABLE 12

Personal Characteristics of Those Individuals More Prone and Those Less Prone to Boredom[73]

Psychological function	Average score		"t" test of significance	"t" at 5% level
	Most bored	Least bored		
1. Intelligence	21.04	16.25	4.20	2.26
2. Divided Attention	14.33	11.03	1.84	2.45
3. Perseveration	119.73	125.13	1.11	2.57
4. Introversion (−) and extroversion (+)	+2.00	−0.63	3.46	2.45

[72] S. Wyatt and J. A. Fraser, *Ind. Health Research Board (London)*, *Rept.* No. **56** (1929).
[73] S. Wyatt and J. N. Langdon, *Ind. Health Research Board (London)*, *Rept.* No. **77** (1937).

2. *Motion Economy*

The problems of motion economy are studied by the mechanical engineer with respect to the use of the human body, arrangement of the work place, and design of tools and machines. The rules concerning the most efficient use of hands in motion were summarized by Barnes.[74]

The experimental approach to the task of determining the optimal patterns of movements can be illustrated by a study of the efficiency of simultaneous symmetrical motions of the two hands when the movements are carried out at different angles to the plane of the front of the worker's body.[75] Two types of motions were used: (*1*) The operator moved hands away from and toward his body, with only the terminal points of the motion being fixed by the work place; this type of movement is performed when the worker reaches for and transports materials from bins in the assembly of small units. (*2*) Both the terminal points and the motion path is fixed; moving levers exemplifies this operation in industrial situations. In the first operation the subject carried back and forth a small wooden block with an electrode connected to a counter; at the terminal points the electrodes had to be inserted into holes that briefly opened and then closed at definite, short intervals. Given a set rate of work, the number of errors (insertions missed) was used as a performance criterion. In task 2 the arrangement was essentially the same, but the motions consisted of pushing a carriage back and forth along fixed slides between fixed terminal points, ten inches apart. Time required for one cycle of motions was used as the performance score.

TABLE 13

Work Efficiency and Direction of Hand Movement[75]

Type of movement	Measurement	Angle[a]			
		90°	60°	30°	0°
Only terminal points of motion fixed	Av. number cycles missed per half-hour work spell	130.6	182.8	247.4	275.0
Both terminal points and paths of motions fixed	Av. time per cycle in *1/1000* sec.	310	294	302	322

[a] Angle of motion path is determined with reference to the front plane of operator's body.

The results are summarized in Table 13. In the first task the number of cycles missed by ten operators per half-hour work period was smallest when both hands moved directly in front of the operator (angle of 90 degrees with the plane of the front of operator's body); also, the fatigue index—determined as the rate of increase in cycles missed per minute—was minimal. When both the terminal points and paths of motion were fixed, the angle of 60 degrees gave the shortest average performance times.

[74] R. M. Barnes, *Motion and Time Study*, Wiley, New York, 1940.

[75] R. M. Barnes and M. E. Mundel, *Univ. Iowa Studies in Eng., Bull.* No. 17 (1939).

This investigation is a typical sample of motion-analysis research carried out by the engineer. The psychologist would insist more on the consideration of individual differences and the validity of determining the "one best way." He would study such factors as the size of the visual field of the subject and the relationship of this characteristic to the accuracy of performance in task 1. Also, he would be interested in the subjective estimates of the ease with which the work can be accomplished and in the onset of the feeling of fatigue.

For measurable physical work, e. g. transporting weights, the physiologist would like to know the "mechanical efficiency" of the motions carried out at the different angles studied. The results, in fact, might be very different for work involving transport of heavier objects; the lateral movements (angle 0°) appear to make smaller demands on the maintenance of posture than the frontal (90° and 60°) movements. Also, he would want to know such characteristics as the velocity and acceleration of the motions and the changes in these characteristics, related to the mode of innervation studied independently by means of electrical action currents.

3. *Time Relationships*

Rate of work. A muscular contraction and the following recovery in rest are physicochemical phenomena taking place in time. Undiminished contractility can be maintained only when the catabolic processes are balanced by the anabolic processes of recovery and when the energy-yielding "fuel" is supplied. In an intact organism a movement that does not perceptibly increase the energy consumption can be repeated for many hours *if* the successive movements are spaced far enough apart. The same movement, e. g. tapping with the index finger, can lead to exhaustion-fatigue in the matter of minutes if the movements follow each other at a fast rate. In industry the determination of the optimal rates of work is an important, not yet satisfactorily solved, problem.

The rate will differ according to the criterion of the "optimum." In terms of production efficiency, the optimal work rate is that which yields the highest daily output and does not result in cumulative fatigue. One must take into account not only the total daily level of output, but also the *shape* of the output curve, the appearance and the degree of fatigue decrement of output. From the biological point of view of the science of human work, the subjective ease of work and the effect of the work day on the individual, his feeling of well-being and his attitudes, his fitness and health, are important as criteria of the "efficiency" of a work regimen.

Physiologically, one way to determine the speed optimum is to find the rate of work that is most economical from the point of view of energy consumption per unit of output. Unfortunately, this method can be legitimately applied only to physical work resulting in a significant rise in metabolism. Crowden[76] by this technique has investigated the optimum rate of wheeling a barrow. Oxygen consumption for identical amounts of useful work accomplished has been determined

[76] G. P. Crowden, *Ind. Health Res. Board (London), Rept.* No. 50 (1928).

for four different speeds of wheeling: a deliberately slow walk, a normal walking pace, a quick walk, and a gentle run. In each case the oxygen consumption has been determined for the whole period of work and of recovery. Taking the values for "normal" walk as 100 per cent the mean percentage values of physiological work cost were 112, 100, 168, and 158, respectively. In this experiment absolute rates of work have not been imposed.

In the Laboratory of Physical Hygiene, University of Minnesota, the efficiency of grade walking was studied at the constant speeds of 2.5, 3.0, 3.5, and 4.0 miles per hour.[77] The "net efficiency" was expressed as the ratio of the calculated caloric equivalent of physical work performed by vertical lifting of the body to the difference in measured energy expenditure between grade and horizontal walking at a given speed. The highest efficiency was reached at the speed of 3.0 and 3.5 m.p.h. Both at the slow (2.5 m.p.h.) and the fast (4.0 m.p.h.) rate of walking the efficiency has decreased markedly. There are similar optima in industrial work, but the actual amount of experimental research and valid information is negligible.

TABLE 14

Net Percentage Efficiencies of Walking on a 5 Per Cent Grade at Various Speeds[77]

Subject	Speed in m.p.h.			
	2.5	3.0	3.5	4.0
A. B.	31.7	35.2	35.0	24.8
D. M.	28.3	37.6	40.3	26.6

Rest periods. A problem related to the rate of work is the question of duration and placement of rest periods. It was the object of the early exploratory work of F. W. Taylor at the Bethlehem Steel Co.[78] He estimated that in heavy muscular work, such as lifting and carrying pieces of pig iron weighing 92 lb. each, a first-class workman can be under load 43 per cent of the work day but must be entirely free from load the remaining 57 per cent of the day if he is to maintain his work capacity; for lifting half-pigs weighing 46 lb. he gives the figures of 58 per cent of the work day under load and 42 per cent of rest, distributed at determined intervals throughout the day.

In introducing short rest periods in industry the aim is to increase the total output, to reduce the subjective feeling of fatigue or both. In work that produces tiredness-fatigue, the insertion of rest pauses provides the recovery time needed for the maintenance of maximal work capacity. In the case of boredom-fatigue, the rest pauses serve to counteract the feeling of monotony. It is true that workers introduce rest pauses spontaneously and develop antidotes to boredom, such as talking, but the optimal length and placement of rest periods can be determined only by systematic experimental inquiry.

[77] L. Erickson, E. Simonson, H. L. Taylor, H. Alexander, and A. Keys, *Am. J. Physiol.*, *145*, 391 (1946).

[78] F. W. Taylor, *The Principles of Scientific Management.* Harper, New York, 1913.

It has been established[79] that in exhausting muscular exercise it is more advantageous to insert a large number of short rest periods than to use a small number of long pauses (see Table 15 for results of an experiment on one subject). Inferences concerning heavy industrial work made on the basis of this type of information can be only tentative.

TABLE 15

Frequency of Resting and the Total Time of Riding a Bicycle Ergometer to Exhaustion With the Total Length of Resting Kept Constant and Equal to Two Minutes[80]

Number of rest periods	Insertion of rest periods	Duration of rest pauses, min.	Time of work to exhaustion after last rest period, min.	Total time of pedaling
1	After 7th minute	2.0	8.2	17.2
4	End of every 3rd minute	0.5	6.5	20.5
8	End of every 1.75 minute	0.25	6.8	22.8
20	End of every 0.9 minute	0.1	5.5	25.5

Graf and Bornemann[80] made experiments on rest periods in light industrial work. The total output was kept the same but the length of the rest periods (and the speed) was varied. In all three arrangements the women operated presses at a regular, prescribed tempo. The work hours were 60 minutes (without a rest period), 55 minutes, and 50 minutes. The last arrangement, which was characterized by the longest rest periods (and fastest rate of work), was preferred by the workers. However, the "quality" of work in this arrangement showed a distinct deterioration during the course of a day; the relative number of errors in the afternoon was consistently larger than in the forenoon. This trend was interpreted as evidence of fatigue resulting from a fast rate of work that was not compensated for by longer rest periods. Work without *any* rest periods was subjectively unpleasant. Thus, under the given conditions, the provision of five-minute rest periods at the end of each hour appeared as the optimal arrangement.

The industrial and laboratory experience of British investigators suggests that in light repetitive work the introduction of a short rest pause of 10 to 15 minutes into each half of the day's work leads to a small but genuine increase in output of the order of 5 to 10 per cent.[81]

Hours of work. Another aspect of the relationship between time and fatigue concerns the length of the workday and of the work week. In relatively light work, such as that involved in operating small punch presses, the lengthening of daily working hours from eight to ten[70] reduced average hourly efficiency from 95.3 per cent to 94.0 per cent of the maximum possible efficiency; the latter (100 per cent) was defined as the highest output attainable if all operators composing the group studied would reach maximum output at the same hour (Fig. 12). On the eight-hour

[79] E. A. Mueller, *Arbeitsphysiol.*, **11**, 211 (1940).
[80] O. Graf and E. Bornemann, *Arbeitsphysiol.*, **11**, 185 (1940).
[81] *Ind. Health Research Board (London), Rept.* No. 27, 14 (1924).

schedule the average hourly efficiency was 94.7 for the first half of the workday and 95.9 for the second half. On the ten-hour schedule these percentages were 94.0 and 94.0 respectively. The drop in the last hour of the two work spells was 3.3 and 5.2 per cent on the short workdays, and 6.2 and 9.3 per cent on the long workdays. This variation in drop indicates a slightly more marked fatigue associated with longer hours of work. The decrement in average hourly efficiency is not too pronounced and the lengthening of the work day, if demanded by an emergency, would bring a significant increase in the total output.

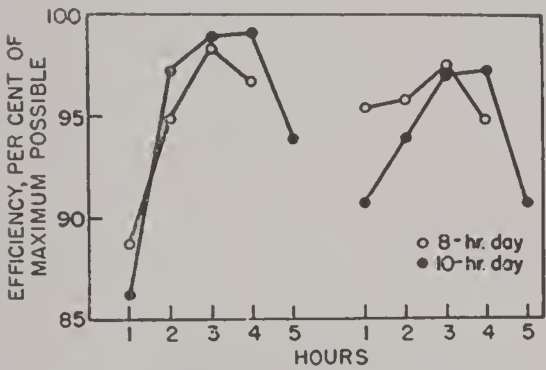


FIG. 12. Relative efficiency (miscellaneous machine work) during an eight-hour and a ten-hour workday.[70]

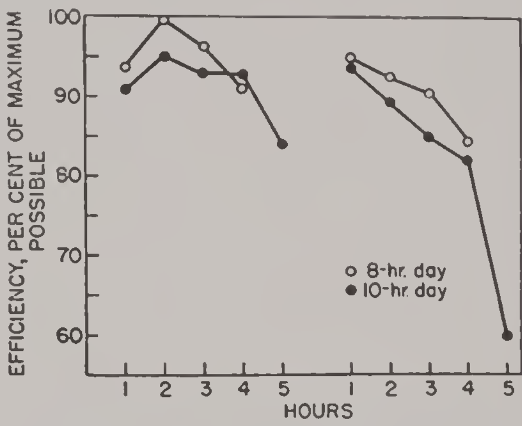


FIG. 13. Relative efficiency (muscular handwork) during an eight-hour and a ten-hour workday.[70]

In work requiring exertion of muscular strength, the average hourly efficiency was 92.8 per cent on eight-hour work schedule and 86.5 per cent on ten-hour schedule (Fig. 13). The averages for the first and second halves of the workday were 95.1 and 90.5, and 91.1 and 81.9, respectively. The presence of greater fatigue on a ten-hour schedule was even more marked when we compare the drop in the last hour of each work spell; the respective decreases below the 100 per cent line are 8.9 and 15.6 per cent on eight-hour days, and 16.1 and 40.1 per cent on ten-hour days. Yet even on the eight-hour schedule the reduction of output in the last hour was considerable. Shorter workdays might be desirable for such operations, particularly if reduction in output were paralleled by pronounced changes in the physiological conditions of the workers and their feelings of tiredness.

4. Between-Meal Feeding

Physiologically, the dietary attempts to reduce or to prevent muscular fatigue and the decrease of performance are concerned with one of the following three processes: renewing the supply of energy-yielding substances; facilitating the energy-yielding reactions; and counteracting the physicochemical changes that accompany the metabolic processes in the working organism.[82]

The argument for introduction of additional meals in the middle of the morning and afternoon shifts is based on the first principle. It has been known

[82] A. Keys, *Federation Proc.*, 2, 164 (1943).

that blood sugar (and the respiratory quotient) rises shortly after a meal and then declines for several hours. If we assume that the blood-sugar level is an index of the availability of carbohydrate for tissue combustion and, secondly, if the thesis could be accepted that the supply of sugar within the range of normal variation is a factor limiting muscular performance, then the argument could be made for efforts to maintain blood sugar at a consistently high level by shortening the periods between meals.

Such an argument has been made by Haggard with reference to industrial situations. He suggested that feelings of fatigue and decreased output observed in some operations toward the end of the a.m. and p.m. work spells may be due to a decreased utilization of carbohydrate and may be relieved by between-meal feeding of food containing readily assimilable carbohydrate. Milk supplemented with breadstuffs or bananas, and canned natural fruit juices were recommended for this purpose.[83]

The experimental evidence is not satisfactory with respect to either the laboratory, or the industrial studies presented in Haggard's and Greenberg's monograph.[84] These authors claimed that the ingestion of a meal and the subsequent rise in blood sugar produced an increase in *mechanical efficiency*, defined in terms of energy consumption in work on a bicycle ergometer, of the order of 25 per cent of the premeal level, or approximately, from 20 to 26 per cent. The relevance of such a change for the majority of industrial operations is questionable; furthermore, the finding itself has been challenged. After ingestion of 20 grams of fructose and of a mixture of glucose and fructose the respiratory quotient (R.Q.) rose from the basal level of approximately 0.78 to 0.86 and 0.90, yet the muscular efficiency in work begun 30 minutes after ingestion was not significantly different from the values obtained in the control experiment in which water alone was taken.[85]

In addition to the laboratory investigations, Haggard and Greenberg studied the relationship of between-meal feeding to industrial production in a plant manufacturing rubber footwear. The operation of sewing together the canvas parts of tennis shoes was selected as the object of the study because it was easy to keep individual hourly production records and there were no important delays in production due to supply of material. The wage system was essentially piece-rate, with a guaranteed minimum wage.

In preliminary experiments on small groups of operators the differences in the hourly production—172 units on two meals, 183 on three meals, 191 on five meals—suggested a significant influence of meals on productivity; in order to explore the problem more thoroughly 40 operators were selected and divided into experimental and control groups. The experiment covered a period of 10 weeks. The control group ate three meals throughout. The experimental group alternated every two weeks between three meals and five meals a day. The two additional meals were supplied without cost to the worker and consisted of a glass of milk and a six-ounce

[83] H. W. Haggard and L. A. Greenberg, *J. Am. Diet. Assoc.*, **17**, 753 (1941).

[84] H. W. Haggard and L. A. Greenberg, *Diet and Physical Efficiency*. Yale Univ. Press, New Haven, 1935.

[85] J. Haldi, G. Bachmann, C. Ensor, and W. Wynn, *Am. J. Physiol.*, **121**, 123 (1938).

piece of angel-food cake; they were served at the beginning of the third work hour both in the morning and in the afternoon. The mean hourly output of the control group varied only slightly from period to period; the experimental group had consistently higher output than the controls when the workers were on a five-meal schedule (Table 16).

TABLE 16

Meal Frequency and Productivity for Periods Representing Ten Workdays Each[84]

	Experimental group				Control group			
Period	No. of meals	Mean hourly production			No. of meals	Mean hourly production		
		Av.	Min.	Max.		Av.	Min.	Max.
I	3	175	169	178	3	183	174	188
II	5	192	188	196	3	184	177	189
III	3	176	171	179	3	183	179	187
IV	5	194	189	196	3	184	179	189
V	3	176	168	178	3	184	180	189

The *fact* that industrial production has increased on the five-meal schedule does not need to be questioned. But the experimental conditions of Haggard and Greenberg do not allow a clear-cut identification of factors responsible for the increased output. The effect of the rest pauses alone, provided by between-meal feedings, and the effect of intake of food of little nutritional value should have been studied to distinguish between the direct, physiological effects of the additional meals and the indirect effects through changes in "morale."

The physiological interpretation of an increased production in terms of high muscular efficiency maintained through more frequent meals is open to question. In *all* p.m. production curves there was a slump followed by a "spurt" at the end of the day although the R.Q. continued to decrease (Fig. 14). This fact indicates that the decrease in output was not related to carbohydrate utilization. Decreased output did not reflect a decrease in the work capacity. The authors have commented that the decline of production "did not signify that the operator was wholly incapable of achieving a greater production by making a greater effort,"[84] but have not incorporated this fact in their general interpretation. For the main experiment the average production rates only, not the hourly output curves, were given.

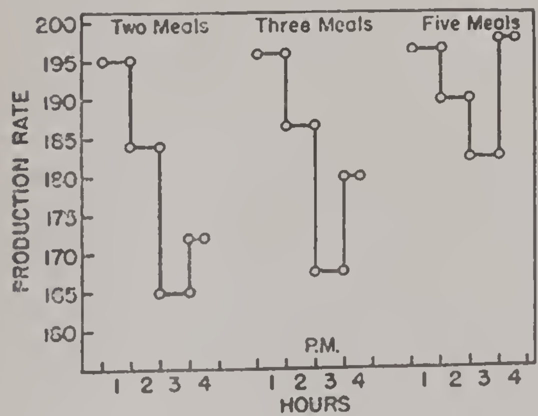


Fig. 14. Average hourly production rates of operators eating different number of meals.[84]

The workers operated power-driven sewing machines; in terms of energy expenditure this represents very light manual work that does not deplete significantly the total energy reserves of the body, and it is hardly conceivable that the work capacity of the muscles could be affected by a variation of blood sugar of the magnitude present three to four hours after a meal.

In describing the general conditions of the experiment the authors were struck by the fact of stable daily output of the highly skilled operators: "They were capable of turning out a production of 100 per cent hour after hour. And what is more, they were able to time themselves so that their production, at the end of the day, was almost exactly 100 per cent, neither above, which might have led to readjustment of the wage scale, nor below, which would have resulted in loss of bonus."[84] We are not informed what has happened to the production of these "100 per centers" on the five-meal schedule. In any case, the restriction of output indicates the presence of social-psychological factors affecting the output records and the necessity for taking them into account in interpreting the results.

The problems of between-meal feeding and its effect on general level of productivity and on the character of the daily output curve is of considerable practical importance. We need further research, both in the laboratory and in industry, before the effects of interim feeding will be well established and clearly understood.

5. *Music in Industry*

In operations that produce boredom-fatigue, talking and singing (as well as daydreaming) are used by the workers to get them "over the hump" of the shift. Wyatt[86] has found a significant negative correlation between the rate of output and the amount of talking in a group of girls engaged in repetitive work such as weighing, wrapping, and packing (see Figs. 15 and 16). The data were obtained under the time-rate system of payment. Both the output and the amount of talking were

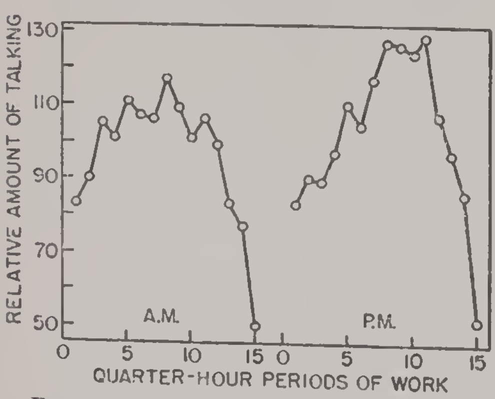


FIG. 15. Daily variation in the amount of talking.[86]

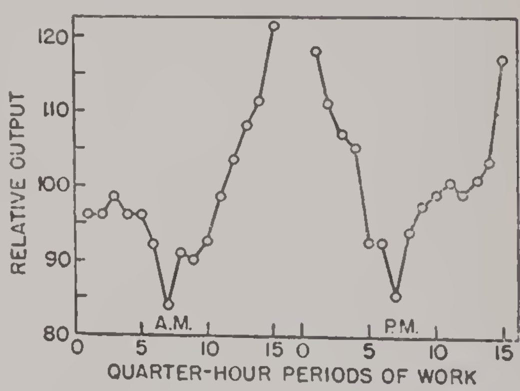


FIG. 16. Daily variation in output.[86]

[86] S. Wyatt, *Ind. Health Research Board (London), Rept.* No. 69 (1934).

recorded in each quarter hour throughout the day and are expressed as percentages of the daily average.

Talking takes the attention of the worker from his work (as well as from himself) and relieves the subjective boredom, but it does not remove the dip in production characteristic of boredom-fatigue. Introduction of "music-while-you-work" has been advocated in order to alleviate the feeling of monotony and at the same time prevent or reduce the production decrement at the middle of the work-spell.

There are good *a priori* reasons why music could do the job and serve as an antidote to boredom. Music, like the "stream of consciousness," flows; it progresses and changes in time. It brings tone sequences that are ever new and fresh, and produces a satisfying esthetic experience. The variation of the basic musical components—melodic sequence, rhythm, tempo, pitch, harmony—provides a practically unlimited possibility for combinations. Much of the musical "language" is generally understandable, and a judicious selection of music played should balance out the individual variations in musical taste, provided the audience and the listening conditions are not too heterogeneous.

Opinion polls and attitude studies indicate that "music-while-you-work" does bring the workers relief from boredom-fatigue. When Kerr [87] asked a group of male technical workers about their feelings concerning music at work, he found them confident that music has beneficial effects. The men ranged in age from 17 to 57, with an average of 24, and were enrolled in a defense training center. The questionnaire contained the following six items: (*1*) What effect does music have on your feelings toward the people around you? (*2*) How does music make you feel when you are tired? (*3*) What effect does music have upon your "nerves"? (*4*) What effect does music have upon your digestion? (*5*) How does music make you feel when you are working at a wearisome, monotonous task? (*6*) What effect does music have upon your worries?

Each item was checked on a 9-point scale, ranging from very favorable to very unfavorable. The responses, grouped into three classes—favorable (points 9, 8, 7, 6), indifferent (5), unfavorable (4, 3, 2, 1)—are summarized in Table 17.

TABLE 17

Summary of Responses of 162 Men to Questions on the Effects of Music[87]

Question No.	Per cent favorable	Per cent indifferent	Per cent unfavorable
1 (Sociability)	76.8	21.9	1.3
2 (Relief of tiredness)	89.7	8.3	2.0
3 (Relief of nervousness)	87.5	11.2	1.3
4 (Digestion)	55.7	41.2	3.1
5 (Relief of monotony)	90.1	5.6	4.3
6 (Relief of worries)	85.1	13.1	1.8

[87] W. A. Kerr, *Psychol. Record*, **5**, 205 (1942).

The questionnaire was also given to a group of 229 electrical workers, 97 per cent of whom were women. The results were surprisingly similar (Table 18). Again, "a majority of the respondents believe that music improves their feelings toward associates, braces them up when tired, soothes their nerves, helps them at wearisome, monotonous work, and makes them forget their worries."[88]

TABLE 18

Summary of Responses of 229 Electrical Workers (97 Per Cent Women) to Questions on the Effects of Music[88]

Question No.	Per cent favorable	Per cent indifferent	Per cent unfavorable
1 (Sociability)	63.8	32.1	4.1
2 (Relief of tiredness)	93.0	6.1	0.9
3 (Relief of nervousness)	79.3	15.0	5.7
4 (Digestion)	47.5	44.3	8.1
5 (Relief of monotony)	89.1	5.7	5.2
6 (Relief of worries)	77.2	16.7	6.1

The effects of introducing music into an industrial situation were studied experimentally by Cardinell.[89] Production was recorded at 15-minute intervals throughout the day; maximum production for each employee, at any one period, was designated as 100 per cent, and the production efficiency in the other periods was expressed as a percentage of this maximum. The production curve had a typical boredom-fatigue shape. In the afternoons, after a short period of a slight increase in production, the efficiency curve started to decline and continued to decline until 2:30, then it began to rise, and rose until 4:00, when it fell again. The program of recorded music was arranged with the aim of reducing or, if possible, eliminating the large mid-shift slump. After preliminary explorations of the most effective placement and length of the music periods, music was introduced from 1:30 to 1:50, from 2:10 to 2:40, and from 3:30 to 3:50. Under these conditions, the production curve did not drop down in the middle of the work period, and the average daily production efficiency rose to 86.8 per cent as compared with 72.0 per cent before the introduction of music (Fig. 17). The weekly average production per 100 man-hours during one week before the installation of music was 301.2 units; during one week after music had been introduced, the corresponding figure was 335.6.

These differences show undoubtedly the maximal results. The effects of industrial music must be studied over a prolonged period of time before the true value of musical programs in industry can be established. Although the output records and other direct criteria of work efficiency are important, attention must be paid also to the effect of music on the attitudes of the workers, both with reference to the musical program itself and also the specific musical preferences. It has been

[88] W. A. Kerr, *Psychol. Record*, **5**, 213 (1942).
[89] Cardinell, *J. Acoust. Soc. America*, **15**, 133 (1943).

shown that an industrial or business audience has different attitudes toward different types of music and that music preferences vary with the occupation.[90]

The effects of a continued musical program on industrial production, its quality and quantity, have been studied in a series of experiments by Kerr.[91] The work was done under actual working conditions and involved repetitive manual operations at workbenches or machines.

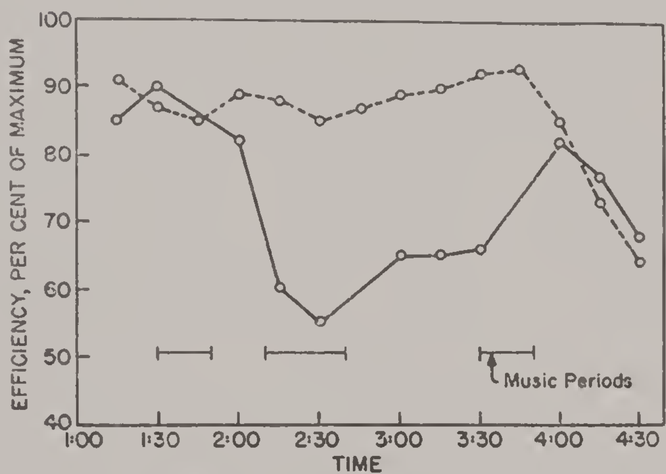


FIG. 17. Effect of music in alleviation of boredom-fatigue (after Cardinell[89]). Diurnal variation in production efficiency before (full line) and after (broken line) music installation on two comparable days.

In one of the experiments production records were kept for 64 women, with a median age of thirty. Of these, 25 women were engaged in roll-assembly, 30 in paper-winding, and 9 in the final can-assembly operation in an R.C.A. plant manufacturing oil capacitors. Ninety per cent of the workers had been exposed to music in the department for at least five months before the start of the experimental period. Variety music was broadcast from 9:00–9:15, 10:15–10:35, 11:30–12:20, and in the afternoon from 1:30–1:45, and 2:45–3:10. In the experimental period, extending over 40 workdays, two days with music were followed by two days without music.

The plant was unionized and there was a group incentive-wage plan in operation. The quantity of production was expressed as "mean per cent efficiency" (total daily earnings divided by total operator hours). In two operations, roll assembly and winding, the efficiency of production was characterized also qualitatively—in the roll assembly in terms of percentage of units rejected by the inspectors per day, and in winding in terms of pounds of scrappage per operator hour. The results (Table 19) indicate that there was a small but consistent increase in the quantity of production on the music days; the quality of production was worse with music, yet, in the case

[90] W. A. Kerr, *J. Acoust. Soc. America*, **15**, 125, (1943).

[91] W. A. Kerr, Effects of Music on Factory Production, *Applied Psychol. Monograph* No. **5** (1945).

where the net good yield was determined, the data still show a slight difference in favor of music. The percentages in rejects and scrappage are "blown up" because rejects and scrappage represent normally a very small percentage of the total output.

TABLE 19

Effect of Music on Production in Three Capacitor Manufacturing Operations[91]

Operation and criterion	Number of days		Mean production		Per cent difference
	No music	Music	No music	Music	
Roll Assembly					
Quantity	18	22	111.67	112.51	0.75
Quality	18	22	−7.78	−8.55	−9.89
Net Yield	18	22	102.32	102.90	0.57
Winding					
Quantity	18	22	132.39	133.72	1.00
Quality	18	17	−.00556	−.00642	−14.00
Can Assembly					
Quantity	18	17	131.61	132.18	0.43

Another experiment was carried out with two groups of workers on the finishing operations of quartz crystal manufacture. The outputs were 4.82 per cent and 7.43 per cent greater with music (56 days) than without music (51 days); scrappage was 8.30 per cent and 2.01 per cent less with music; the number of employees in the two groups was 40 and 6, respectively; the pay was on a straight hourly basis. This is probably the maximum that can be expected from an industrial musical program maintained over a long period of time.

On the basis of available data we can say that music *is* a "production tool," relieving the effects of monotony and increasing production by leveling "boredom slumps" in the output curves. The principal points derived from industrial experience and experimental research work may be thus summarized, following in the main Kirkpatrick[92] and Kerr[93].

(*1*) Music-while-you-work is most effective for repetitive manual jobs. (*2*) It should be "turned on" only for short periods and at times when boredom depresses the output. (*3*) Two or three periods of music of about 30 minutes each seem to produce the most satisfactory results. (*4*) Large variations in the intensity of the music played are irritating and distracting. (*5*) The intensity of the music has to be adjusted to the noise level of each work room. (*6*) Musical preferences of industrial audiences, gaged by standard attitude scales, should be taken into account in planning music programs. (*7*) Work involving a significant mental component may be hindered rather than aided by music.

[92] F. H. Kirkpatrick, *Psychol. Record,* **5**, 197 (1942).
[93] W. A. Kerr, *J. Psychol.,* **17**, 243 (1944).

IV. Problems of Maintenance

In addition to the problems of selection and of reduction of fatigue developed within the period of the workday, we are concerned with the task of long-term maintenance of an efficient labor force. On the physiological level the question of industrial nutrition recently received much attention. Psychologically, prevention of personal (individual) maladjustment is an important aspect of maintaining occupational fitness. Finally, industrial production involves interaction between different individuals and groups of individuals, and the social factors affect significantly both the actual level of output and the flow of work; poor "morale" resulting in restriction of output or a strike can offset all the improvement of productivity resulting from the consideration of physiological and individual-psychological factors.

A. NUTRITION

Provision of adequate diet for industrial workers is considered as one component of the preventive phase of industrial medicine.[94] It is a generally accepted thesis that well-balanced food in sufficient amounts is necessary for the maintenance of physical fitness, mental alertness, feeling of well-being, and efficient work performance. When we ask specific questions about "requirements" for different dietary components (proteins, fats, carbohydrates, minerals, vitamins, water, roughage) the answers are less categorical. The extensive literature on physical performance in relation to diet has been reviewed by Keys.[95] Yet strictly controlled studies on the relationship of nutritional factors and industrial work efficiency are nonexistent, and even laboratory studies having bearing on capacity for ordinary industrial work are very few. The stores of dependable knowledge in this area are smaller than one would expect.

The topic of industrial nutrition will be discussed under the headings of calorie requirements, special dietary requirements, and in-plant feeding.

1. Caloric Requirements

The calories required are related to the intensity of metabolism. If there is an increase in any of the components of the total body metabolism—basal metabolism, static work, dynamic work—an increased food intake will be required to maintain a constant body weight. It is estimated that the adult man of average weight (70 kg.) doing moderate work expends about 3000 Calories per 24 hours; the daily caloric requirement for an average woman (weight of 56 kg.) is estimated as 2500 Calories. The majority of jobs in modern industry will not cause much deviation from this average.

2. Special Dietary Requirements

In the majority of industrial operations the physical work involved does not increase drastically the energy consumption, so that the calorie value of the diet is

[94] W. A. Sawyer, *Med. Clin. N. Am.*, **26**, 1067 (1942).
[95] A. Keys, *Federation Proc.*, **2**, 164 (1943).

rarely considered, at least in the United States, a serious limitation in nutrition. It is the quality of the food, the adequacy of its components from the physiological point of view, that is the concern of the nutritionist. The best current criteria of "adequacy" of a diet are the dietary allowances[96] recommended by the National Research Council (see Table 20).

TABLE 20

Recommended Dietary Allowances[96]

Item	Man			Woman		
	Sedentary	Moderately active	Very active	Sedentary	Moderately active	Very active
Calories	2500.0	3000.0	4500.0	2100.0	2500.0	3000.0
Protein (g.)	70.0	70.0	70.0	60.0	60.0	60.0
Calcium (g.)	0.8	0.8	0.8	0.8	0.8	0.8
Iron (mg.)	12.0	12.0	12.0	12.0	12.0	12.0
Vitamin A (I.U.)	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0
Thiamine (mg.)	1.2	1.5	2.0	1.1	1.2	1.5
Riboflavin (mg.)	1.6	2.0	2.6	1.5	1.6	2.0
Niacin (mg.)	12.0	15.0	20.0	11.0	12.0	15.0
Ascorbic acid (mg.)	75.0	75.0	75.0	70.0	70.0	70.0

These recommended allowances provide for the "minimal requirements," plus a margin of safety. When moderately active, normal young men were maintained for 161 days on a controlled B-vitamin intake of 0.185 mg. of thiamine, 0.287 mg. of riboflavin, and 3.71 mg. of niacin per 1000 calories, considerably below the N.R.C. allowances, the restriction produced only trifling indications of dietary inadequacy, such as a very slight increase in the blood pyruvate, slight increase in conscious control and "vigilance" over their behavior reflected in the Rorschach records, and slightly smaller practice improvements in two out of eight measures of voluntary motor performance.[97,98] The fact that the criteria of "fitness" used in this investigation are sensitive to a true vitamin deficiency was established when the subjects were subsequently placed on diets practically free of the vitamins of the B complex (0.008 mg. of thiamine, 0.013 mg. of riboflavin, and 0.100 mg. of niacin per 1000 calories). Nausea and vomiting appeared within two weeks. The average depression score of the deficient subjects on the Minnesota Multiphasic Personality Inventory (normal average = 50, standard deviation = 10) rose from 58 to 89. The average score on the test of gross body reaction time increased from 61/120 second to 98/120 second, while the corresponding scores obtained on the fourth and twenty-third days of the "deficiency period" for the control group were 73/120 second, and 76/120 second. The number of errors in a test of eye-hand co-ordination rose from 26 to 42; in the control group there was an improvement of performance characterized by the decrease of errors from 28 to 17.

[96] *Natl. Research Council, Reprint and Circular Series* No. 122 (1945).

[97] A. Keys, A. Henschel, H. L. Taylor, O. Mickelsen, and J. Brozek, *Am. J. Physiol.*, **144**, 5 (1945).

[98] J. Brozek, H. Guetzkow, O. Mickelsen, and A. Keys, *J. Applied Psychol.*, **30**, 359 (1946).

In a number of nutritional surveys the interpretation of the raw findings became totally misleading because of the fatal identification of "requirements" and "allowances" *recommended* by the National Research Council. Thus, when in a group of 250 aircraft workers the content of the diet was estimated, the riboflavin content varied from 0.45 to 2.10 mg. per 1000 calories, with a median value of 0.75. The recommended allowance was 0.90 mg. per 1000 calories. On the basis of this comparison and the data on the estimated amounts of vitamin A, thiamine, and ascorbic acid, the conclusion was drawn that "riboflavin is still one of the most frequent deficiencies, second only to ascorbic acid."[99] According to the 1945 revision National Research Council allowances, Wiehl's median value coincides, and in fact slightly exceeds, the recommended level.

It has been pointed out[100] that dietary requirements cannot—any more than any other human biological characteristics—be represented by a single value, but, must be represented by a range of values around the population average. This is true if we think either in terms of "minimal" requirements, defined as the intake level necessary to prevent appearance of pathological changes, or in terms of "optimal" intakes, however these may be determined. If the dietary requirements are expressed as averages, it follows *by definition* that half of the population needs *less* than the average. To label without further clinical studies such an intake level as "deficient" is plainly incorrect. The task of determining whether individual requirements are matched with adequate individual intakes is an important but neglected part of dietary surveys. The definition of the standards in the National Research Council recommended allowances is not quite clear although it has been stated in a general way that, the "standards of dietary essentials are average."[101]

The effects of hard work upon nutritional requirements have been summarized by Forbes.[102] It appears that physical work increases primarily the need for calories. The requirements for protein and vitamins A, D, C, and K are increased only slightly, if at all. The need for the vitamins of the B complex is increased, though probably not as steeply as the caloric requirements. As far as acceptable scientific evidence goes, "Nothing is known of the extra requirements, if any, for the kind of work that the average industrial worker performs, namely, work which is physically easy but nervously or emotionally tiring."[102]

The problem as to whether the improvement of nutrition serves as a protection against industrial poisoning may be an interesting and fertile field for research, but the available evidence is limited.[103] For chronic cases of lead poisoning a diet rich in calcium has been recommended. Prophylactic use of low-fat diet in workers exposed to the danger of nickel poisoning appears promising. Vitamin C seems to increase resistance to benzol and TNT poisoning. However, in general the bearing of

[99] D. G. Wiehl, in *New Steps in Public Health.* Milbank Memorial Fund, New York, 1945.

[100] L. B. Pett, *Can. Pub. Health J.*, **36**, 69 (1945).

[101] *Natl. Research Council Bull.* No. 109, 19 (1943).

[102] W. H. Forbes, in *New Steps in Public Health.* Milbank Memorial Fund, New York, 1945.

variations in nutritional status "on resistance to toxic environment has not yet been sufficiently investigated and certain deductions must be made largely by analogy."[103]

3. In-Plant Feeding

During the war a large number of plants made provisions for in-plant feeding. The idea was a good one and should be kept up. The food, particularly the lunches of the industrial workers, did not appear to measure up to the best standards. Four major factors potentially producing nutritional deficiencies were suggested: (*a*) poor food habits leading to consumption of inadequate amounts of biologically valuable foods and to an excessive consumption of candy, sweet carbonated beverages, and alcohol; (*b*) difficulties the consumers had in obtaining foodstuffs rich in the protective foods; replacement of whole wheat flour by highly-milled grain products belonged to this category; (*c*) low family income limiting the purchasing power; and (*d*) increase in metabolism in such conditions as fever, work under extremes of temperature, lengthened working hours, where increased energy expenditure is not balanced by a parallel increase in food intake.[104]

For the purpose of promoting proper eating conditions and of serving nutritious foods to industrial workers, a manual was prepared containing suggestions for in-plant feeding menus and materials for an educational campaign, including posters, pamphlets, films, and radio scripts.[105]

B. Personal Adjustment

In the work of an industrial psychiatrist three tasks stand out: (*1*) his share in screening out the totally unemployable who must be taken care of in other than industrial environment, (*2*) therapy of individual cases of maladjustment, and (*3*) preventive measures. In addition, there are other tasks. New employees should be placed at jobs that match not only their aptitudes, but also their personalities; systematic psychiatric work in this area is practically nonexistent. There is a need for the development of sheltered workshops, comparable to those for the physically handicapped, for employees who can be saved for the industry and for society at large if special work conditions and supervision are provided. In order to do this effectively we should know much more than we do now about the incidence of neuropsychiatric disturbances in different types of work and the effect of working conditions, such as the length of the work week, shifts, etc., on personal adjustment.[106] Psychiatrists' help should be valuable in dealing with "chronic hospital users" for whom illness serves as an alibi for failure on the job and in their social life, or as a sympathy-getting mechanism; in handling the "sick leaves" of employees

[103] W. E. Crutchfield, Jr., in *New Steps in Public Health.* Milbank Memorial Fund, New York, 1945.

[104] *Natl. Research Council, Reprint and Circular Series* No. *110*, 9–11 (1942).

[105] Food Distribution Administration, *Manual of Industrial Nutrition.* U. S. Govt. Printing Office, 1943.

[106] L. S. Kubie, *Mental Hyg.*, *29*, 201 (1945).

who present no evidence of physical illness; and in diagnosing and treating weariness-fatigue cases in which emotional factors are involved.[107]

In view of the importance of work adjustment for the total adjustment of an individual, it is desirable to reduce the emotional tensions between the worker, his job, and his human work environment. An intensive feeling of boredom can be referred to as an individual-emotional problem, whereas the tension due to a resentment against the foreman belongs to the category of interpersonal or socio-emotional maladjustment. The "extramural" factors leading to or aggravating personal maladjustment have to be considered also. The extent of this problem in industry is anything but trifling. It is estimated that in large organizations, at any one time, about 20 per cent of the employees suffer from some type of emotional disturbance.[108]

McMurray describes five types of personality maladjustment frequently encountered in industry.[109]

(*1*) Excessive preoccupation with the self. The withdrawal from social reality may vary widely. It may be accompanied by preoccupation with health (hypochondriacal tendencies) and aggravated by beliefs that the individual is being persecuted (paranoiac tendencies).

(*2*) Aggressive tendencies directed against the individual himself. Excessive and groundless anxiety, some types of accident proneness, alcohol and drug addiction, and self-induced failure belong to this category.

(*3*) Attacks on the things and persons of the work environment, be they one's associates, superiors, or subordinates (sadistic tendencies).

(*4*) Inability to find or hold a job because of a deep-seated desire for passivity and infantile dependence or because job failure is a means of revenge on one's family.

(*5*) Feelings of insecurity and inadequacy compensated for by bravado, boasting, or living beyond one's financial means.

Although the problems of severe mental illness in industry deserve attention, there is a pressing need for assistance in cases of minor, but potentially dangerous, emotional difficulties. These are conspicuous by their frequency rather than by the degree of the deviations from normality. The rapid expansion of industry in World War II and the many personal difficulties of the new workers, including such problems as transportation and housing, led to a rapid development of "employee counseling" programs. We share Cantor's apprehension that the sound idea of helping the worker with his personal problems might be discredited by an inadequate consultant staff.[110] The demand for employee counselors expressed a real need. It is apparent that there is not and will not be available a proportionate number of trained psychiatrists. Graduate training combining the viewpoint and

[107] V. V. Anderson, *Psychiatry in Industry*. Harper, New York, 1929.

[108] L. G. Giberson, *Med. Clin. N. Am.*, **26**, 1085 (1942).

[109] R. N. McMurray, *Handling Personality Adjustment in Industry*. Harper, New York, 1944, p. 76–100.

[110] N. Cantor, *Employee Counseling*. McGraw-Hill, New York, 1945.

techniques of clinical psychology and psychiatric social work, with realistic field work in industry, appears as the ideal background for the industrial counselor of the future.

The serious problems of personal maladjustment are the professional concern of a psychiatrist. Yet the attempt to deal with these problems singlehandedly by the techniques of "office psychiatry" is in the majority of instances doomed to failure. The co-operative approach is the only workable alternative. Frequently there is need for psychometric evaluation. The actual placement or replacement of an individual is carried out by the personnel man who contributes his knowledge of the human and physical work environment. There are also the problems of industrial training and education. The psychiatric social worker assists the employees in coping with out-of-plant difficulties. The management, from the foremen to the top officers, should be "mental health conscious" and should apply the principles of mental hygiene in the large personnel policies as well as in the handling of individual cases.

An effective mental health program cannot be limited to the emotional health of the individuals, but must respect the importance of the interpersonal relationships and be concerned with the improvement of the human environment of the worker. Because of the frequency of personal contacts with the employees, the foreman's skill in handling people is one of the critical links in the maintenance of mental health in industry. In training the foremen to deal with problems involving personal relationships, group lectures and conferences can be effectively supplemented by consultation of the psychiatrist or the clinical psychologist with the foreman in specific cases presenting adjustment difficulties.[111]

The need for increased attention to mental health is being appreciated more and more by progressive plant physicians. At the same time a greater individual happiness and personal effectiveness can well be identified with the basic objectives of the organized labor movement. Labor's goal of a program of mental health in industry is "to establish the dignity of the worker as a human being, to develop his or her personality, to safeguard his or her individuality, and to provide compensating cultural opportunities sufficient to offset the monotony of pushing buttons and pulling levers . . ., to open up to the worker avenues through which to express his or her talents and capacities, so that they can feel that their job is important to themselves and to society."[112]

Occupational adjustment and maladjustment and satisfaction or dissatisfaction derived from work contribute to the general mental health of the individual and, indirectly, to his physical fitness. In recent years attention has been called repeatedly to the role of emotional and social factors in illness.[113, 114] It is known that intensive

[111] L. E. Himler, *Mental Hyg.*, **29**, 106 (1945).
[112] C. W. Fountain, *Mental Hyg.*, **29**, 95 (1945).
[113] E. Weiss and O. S. English, *Psychosomatic Medicine*. Saunders, Philadelphia, 1943.
[114] G. C. Robinson, in *New Steps in Public Health*. Milbank Memorial Fund, New York, 1945.

mental stimuli are paralleled by physiological changes, by changes in tension of smooth and striated muscles, in circulation and respiration, in secretion and such aspects of body chemistry as the blood-sugar level. When the disturbance of a function is prolonged, chronic structural changes may result. Dunbar[115] cites as simple examples the muscular atrophy resulting from chronic contraction of the limbs in catatonia, cardiac hypertrophy following prolonged hypertension, and hemorrhoids resulting from chronic constipation.

Wolf and Wolff studied experimentally the relationship between emotional states and gastric functions including stomach motility, secretion of gastric juice, and the color of the mucous lining of the stomach, which reflects changes in blood flow.[116] Some of the emotionally charged situations were induced experimentally. The experimenters knew that the subject resented hypodermic injections. When he was given a hypodermic injection of 1 cc. of sterile water, the redness of the mucosa increased 10 points on the color scale (from 55 to 65) within 15 minutes after the injection and returned to normal within 45 minutes. The resentment was also associated with an accelerated secretion of hydrochloric acid. The readings, in cubic centimeters of HCl per half hour, were approximately 2, 4, 5, and 3 at intervals of 0, 15, 30, and 45 minutes after the injection. When the subject was asked to do mental arithmetic, the task produced feelings of embarrassment; at the same time "he blushed both in his face and his gastric mucosa, and there occurred a moderate acceleration of acid secretion."[116]

Of particular interest are the studies of the effects of sustained emotional tension. While the average HCl secretion per half hour was 3.6 cc. and the redness index 46 for 3 weeks of the control period, these values rose to 5.5 and 53, respectively, during 2 weeks of domestic conflict.

A prolonged hyperacidity of the stomach is accompanied with hyperemia and engorgement of the mucosa. The mucous membrane becomes more susceptible to injury in the form of hemorrhages and erosions that may result in formation of a peptic ulcer. This is a clear-cut case of structural damage resulting from functional, physiological alterations, which may be traced in their turn to emotional stresses.

In a large sample of patients encountered in the outpatient department of a general hospital, about 65 per cent were confronted with adverse social conditions that caused emotional disturbances in over 50 per cent of the total sample and were regarded as the major cause precipitating illness in about 36 per cent of the cases.[114] There are no comparable figures for an industrial population. There is little doubt, however, that the figures would be high, also, particularly in periods of threatening economic crises. Consideration of emotional factors of illness leads directly and logically from concern with the health of the individual to pathogenic factors in his surroundings and to human relationships, and from clinical to preventive medicine.

Two illustrative cases of illness as related to human relationships in industry,

[115] F. Dunbar, *Psychosomatic Diagnosis*. Hoeber, New York, 1943.

[116] S. Wolf and H. G. Wolff, *Human Gastric Function*. Oxford Univ. Press, New York, 1943.

described by Robinson,[117] will be cited. Antagonism against a new supervisor, who appeared to apply the high-pressure methods of an "efficiency man," led to a development of disabling abdominal pains in a seasoned and previously successful shoe worker. Careful physical examinations including laboratory procedures revealed no pathology and drug treatment was ineffective. A psychiatric interview revealed the intensive emotional strain preceding the onset of symptoms, and the success of psychotherapy in removing the symptoms confirmed their psychogenic nature. In this case the emotional strain could be understood only in terms of the social context of the patient's work. In another case, that of a laundry worker, conscientious but of limited executive ability, the promotion to a position including supervisory duties produced emotional tension resulting in serious circulatory disturbances. Transfer to a job in which she was responsible only for her own work produced rapid relief of the symptoms.

C. MORALE

Industrial "morale" includes not only personal factors such as adjustment or maladjustment of the individual worker, but also factors arising from the interaction between the worker and his job environment, both physical and social. Economic factors enter in, too. Thus, introduction of greater job security by means of providing all-year-round work and stabilizing income represents an important step in building and maintaining work morale. The Nunn-Bush Shoe Company in Milwaukee, Wisconsin is one of the plants that did original thinking and planning in the attempt to stabilize the ratios between sales, production, and employment. The first principle of their plan was that wages are proportional to profits. Secondly, each employee who worked with the company for two years was given a drawing account from which he drew 52 pay checks a year regardless of layoffs due to seasonal variation in production. The weekly checks were based on the estimates of the company's gross income and were adjusted periodically according to the volume of business. The plan permits employees "to manage their personal affairs in an orderly fashion. They do not have to worry about unexpected layoffs and complete cessation of wages. Annual wages for the factory workers have increased under the new plan and the factory has gained better, more dependable employees as the natural result."[118] Progress along similar lines has been made at the large meat-packing plant of Geo. A. Hormel & Co., Austin, Minn. It is unfortunate that experiments of such great social significance were not subjected to a comprehensive scientific study.

The stability and the general level of wages in relation to the actual purchasing power of the dollar and to wages prevalent in the community is important. But inequality of wages, the lack of internal consistency of wage policy in the plant, is frequently an even more acute source of dissatisfaction. In an attempt to eliminate unfair pay differentials one has to determine (*1*) the maximum-minimum worth of

[117] Natl. Research Council Committee on Work in Industry, *Fatigue of Workers*. Reinhold, New York, 1941, pp. 45–55.

[118] C. A. Koepke, *Plant Production Control*. Wiley, New York.

the job within the industrial organization, and (*2*) the quality of performance of the man on this job.[119] The four basic job characteristics to be considered are skill, responsibility, effort, and work conditions, and these characteristics can be subdivided and refined according to the complexity of a job. Moore[119] has emphasized the need for co-operation of management and labor in developing the program. The principles on which the wage structure is built must be understood and accepted by both if the efforts of the job analyst and wage setters are not to be wasted.

The desire for security together with the desire for self-assertion are two fundamental motives affecting industrial morale. Employee-retirement plans, health and accident insurance, and a guaranteed annual wage promote the sense of financial security. Psychologically, the "atmosphere of approval," the clear knowledge of the company's general policies and specific regulations, and of the employee's responsibilities and privileges, and a consistent discipline contribute to an increased feeling of security. On the positive side, loyal and active collaboration is enhanced by giving the employee an opportunity to contribute suggestions to the solution of technical problems, by delegating to him an appropriate amount of responsibility, and by allowing him the right of appealing the important decisions of his immediate supervisor to a higher level of the industrial organization.[120]

In settling "labor troubles" an effective remedial program can be planned only if the major causes of employee dissatisfaction operating in the given situation are known. The source of labor unrest may be dissatisfaction with wages, working hours and changing of shifts, working conditions, eating arrangements; there may be faulty supervision and inadequate machinery for transmitting the complaints "up the line" and for remedial action. It has been stressed that "the study should not be limited to such major issues as wages, hours, and privileges, but should include the search for and discovery of the trifling annoyances, the petty irritations, and the irksome frustrations to which the employee is repeatedly subject in his daily work."[121]

McMurry lists—in a different order—six methods of obtaining information about employee attitudes toward the company and its policies: (*1*) Discussion of grievances at the meetings of the labor management committees. (*2*) The exit interview of all the employees who leave the company. (*3*) Use of special counselors-investigators connected with the personnel department but without executive authority, who periodically have confidential interviews with the employees. (*4*) Use of a "father confessor" who would have a similar role to that of the "counselors," only still more informal. (*5*) Interviews of a sample of the employees in their homes. The anonymity of the individuals interviewed is safeguarded by recording their answers to a standardized questionnaire by tally marks on a single master sheet. (*6*) Systematic survey of the employees' opinions and attitudes.

The employee opinion polls can serve as useful "morale barometers," provided

[119] H. Moore, *J. Consult. Psychol.*, **8**, 90 (1944).

[120] D. McGregor, *J. Consult. Psychol.*, **8**, 55 (1944).

[121] R. N. McMurray, *Handling Personality Adjustment in Industry*. Harper, New York, 1944.

the employee has complete assurance that his statements will not in any way be used against him. For this reason it is preferable to have the polls taken by outside investigators. When the polls are repeated at intervals, "management is able not only to detect incipient trouble, but also to obtain a running measure of the extent to which the changes it is instituting are productive of improvements in morale."[121]

Uhrbrock's investigation[122] may be taken to illustrate the study of morale by means of attitude-measurement scales. Numerous statements expressing positive, neutral, and negative attitudes were assembled and rated by a large number of judges. In the final attitude scale only fifty statements were retained; their numerical value ranged from 0.6 to 10.5. Three examples of the scale items, with their scale values, will be given:

Scale Value	Item
10.4	I think this company treats its employees better than any other company I know.
5.1	The workers put as much over on the company as the company puts over on them.
1.0	The pay in this company is terrible.

The over-all level of the attitude of an employee to the company is indicated numerically by the average value of the items that the workers check as "true." The respective mean scale values for 400 foremen, 96 clerks, and 3,934 factory workers were 7.19, 6.89, and 6.34; the differences were statistically highly significant. There was also a statistically significant difference between men (mean = 6.30) and women (mean = 6.62). Long service with the company was only slightly associated with more favorable attitudes.

Aptitudes are essentially static, but attitudes are subject to changes, both in the positive and the negative direction. The creation and maintenance of favorable attitudes on the part of the employees is, therefore, one of the essential responsibilities of management.

TABLE 21

Reasons for Satisfaction in Work (N = 157)[123]

Reasons	Percentage
Work identical with vocational aspiration	29
Congenial work conditions and social contacts	24
Initiative, responsibility, and prestige	19
Variety of tasks	12
Opportunity for promotion	8
Short working hours	4
Salary	4
Total	100

[122] R. S. Uhrbrock, *J. Soc. Psychol.*, **5**, 365 (1934).
[123] J. M. Seidman and G. Watson, *J. Consult. Psychol.*, **4**, 117 (1940).

Unprejudiced scientific analysis of tense labor relationships may reveal that the weight of different factors contributing to the satisfaction or dissatisfaction of the workers may be very different from that assigned to them by industrial lore. The fact that the activities of the organized labor movement are so largely focused on improving the workers' economic situation, together with the prestige money has in our culture, leads frequently to thinking of wage raising as the panacea of industrial unrest. Yet the studies of job satisfaction indicate decisively that wages play a smaller role than would be expected.[123]

A group of 157 unemployed young men, American-born, unmarried, between the ages of 16 and 24, when questioned about the reasons why one job they held before was most appealing to them, gave the answers shown in Table 21.

The importance of factors contributing to employees' satisfaction that comes with the recognition of each employee *as a person* was demonstrated in the study of Hull and Kolstad.[124] They measured the general employee morale by a questionnaire containing 10 items, such as "To what extent are you made to feel that you are really a part of the organization?" or "Generally speaking, how does the Company compare as a place to work with other companies that you know about or have worked for?" The respondent checked one of the five graduated answers. The total maximum score was 100 points. The mean score for a sample of about 44,000 cases obtained by combining 141 separate groups of rank-and-file employees was 69.7.

TABLE 22

Average Scores of General Morale (Maximum Score = 100) in Reference to Satisfaction with Selected Specific Factors in the Job Situation[124]

Specific factor	General morale score of		Difference
	Satisfied	Not satisfied	
1. A fair hearing and square deal on grievances	80.2	59.8	20.4
2. The prospect of a satisfactory future	80.4	61.6	18.8
3. Company's knowledge of the employee's qualifications and progress	78.9	60.7	18.2
4. Recognition of and credit for constructive suggestions offered	78.1	60.4	17.7
5. Friendly and helpful criticism of work or correction of errors	77.8	60.1	17.7
6. Pay increases when deserved	83.4	66.8	16.6
7. Recognition or praise for unusually good work	82.4	66.2	16.2
8. Selection of best-qualified employee for promotion when vacancies arise	84.7	68.7	16.0
9. Amount of work required not unreasonable	77.1	62.5	14.6
10. Pay at least as high as elsewhere for the same type of work	79.0	64.5	14.5
11. Freedom to seek help when difficult problems arise in work	79.8	65.5	14.3
12. Freedom from unjust reprimand	80.2	66.4	13.8
13. Satisfactory daily working hours	77.4	64.3	13.1
14. The company's vacation policy	80.8	68.7	12.1
15. Approval of the company's employee magazine	77.1	72.2	4.9

[124] R. L. Hull and A. Kolstad, in *Civilian Morale*. Reynal and Hitchcock, New York, 1942.

The relationship to general morale of attitudes on specific topics, such as satisfaction with handling of grievances, was studied by computing the average general morale score for those who were satisfied and for those who were dissatisfied with the particular aspect of personnel policy; the size of the difference indicates the relative importance of the specific factor to general morale. The results for a group of more than 10,000 department store employees located in various parts of the country are summarized in Table 22.

The study of Hull and Kolstad points out how large a part immediate supervision plays in determining employee morale. Furthermore, the satisfaction or

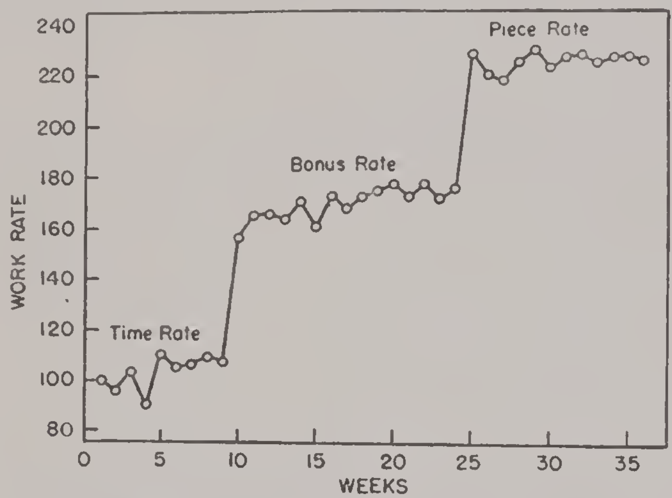


FIG. 18. Effect of different systems of payment on rate of improvement and average level of output for 10 young women employees.[125]

dissatisfaction engendered through the contacts with foremen or department managers carries over to factors that are not controlled by the immediate supervisor. A company with a number of similar departments is cited as an example. In the first department 71 per cent felt satisfied with the handling of grievances, in the second department only 23 per cent did; the percentages of workers who thought the people immediately above them were fair in their treatment of the employees were 54 per cent and 11 per cent, respectively; the percentages of employees believing that they were not reprimanded unjustly were 61 per cent and 14 per cent; on the average, the two departments differed 26 points in their morale scores. At the same time, 61 per cent of the workers in the first department and only 37 per cent in the second department felt satisfied with the rate of pay, *although both departments had identical basic rates of pay and identical physical working conditions.*

"Under these circumstances it would seem impossible to create high morale in the second department by means of pay increases, shorter hours, longer vacations, better physical working conditions, or any of the other tangible considerations which are so often the points of issue at labor disputes. Yet it can readily be seen that those employees might express their low morale in terms of such demands."[124]

[125] S. Wyatt, *Ind. Health Research Board* (London), *Rept.* No. 69 (1934).

Actual output level, under ordinary circumstances, is always below the attainable maximum. Various schemes[125] were developed to set, by means of financial incentives, the "level of aspiration" closer to the working capacity. The effects of three systems of pay—time rate, bonus rate, and piece rate—are reflected in Figure 18. However, output is not the only criterion of "efficient" work conditions. It is significant that the frequency of *complaints* for comparable periods of work rose steadily from 2.9 under the time-rate system of payment to 7.1 under the bonus-rate and 10.8 under the piece-rate. These findings are relevant for consideration of the effectiveness of various systems of pay in reference to long-term efficiency.

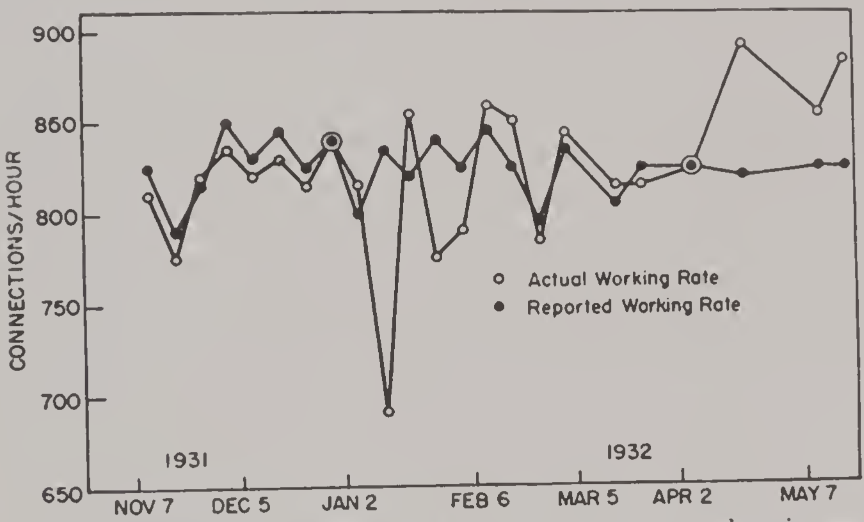


FIG. 19. Actual *vs.* reported average hourly output per week—wireman No. 6.[126]

Even the technically perfect system of wage incentives may become completely ineffective if it clashes with the more basic interests of the workers. This fact was brought out very clearly by research at the Hawthorne plant of Western Electric Company in Chicago.[126] In the wiring-observation room the reported output rates were much more regular than the actual rates of output. Figure 19 indicates that the worker attempted to maintain a steady level of output and to achieve this goal reported output smaller or greater than the actual. The ideal of "straight-line" output curves was shared by other workers. They were afraid that large variations might cause trouble: a high output would indicate that they were capable of performing better than they do, whereas a low output might bring unfavorable comments from the supervisor. The work record given in Figure 19 is a typical industrial sample of social or socialized behavior, which is defined as behavior in accordance with the expectations and sentiments of some other person or group of persons.[127]

[126] F. J. Roethlisberger and J. Dickson, *Management and the Worker*. Harvard Univ. Press, Cambridge, Mass., 1940.

[127] F. J. Roethlisberger, *Management and Morale*. Harvard Univ. Press, Cambridge, Mass., 1941.

TABLE 23

Check List of Measures to Reduce Absenteeism[128]

I. HEALTH AND SAFETY

1. Pre-employment medical examinations
2. Prevention of respiratory infections
3. Convenient lunch facilities with well-balanced foods
4. Sufficient time allowance for meals
5. Nutrition information for employees' families
6. Proper ventilation
7. Proper sanitation
8. Plant medical supervision
9. Plant nurses
10. Adequate safety devices and instruction
11. Adjustment of work schedules to prevent cumulative fatigue
12. Check-up of reported sick absences

II. MORALE

13. Appraisal of applicants' aptitudes and responsibility
14. Pre-employment explanation of rules and relation to war effort
15. Information about relation of individual job to war
16. Instruction of foremen on methods of maintaining morale
17. Use of visitors from armed forces
18. Information about ex-employees in service
19. Monetary incentives
20. Incentives other than monetary
21. Plant posters and other exhibits

III. ADJUSTMENTS FOR PERSONAL OR FAMILY NEEDS

22. Housing arrangements
23. Transportation arrangements
24. Time off for attending to household or personal duties

IV. CO-OPERATION

25. With labor through special committees
26. With community as to (a) housing
27. (b) transportation
28. (c) day nurseries
29. (d) store and shop hours
30. (e) health program

Absenteeism, especially in the sense of nonauthorized, nonsickness absences, is one index of low morale. Reducing absences from work to the minimum is a part of the complex task of maintaining production efficiency and has to be approached from the point of view of over-all industrial administration; no simple panacea can be hoped for. The Industrial Relations Department of the National Association of Manufacturers has prepared an extensive list of items related to absenteeism (Table 23). The items reflect war conditions, but the list should be helpful in pointing out the complexity of the problem and in emphasizing the human relations aspects of it.[128]

Absenteeism, both involving and not involving sickness, is in general larger for women than for men. In fourteen companies studied during the year 1941 there were 83.1 absences per 1000 men and 104.6 per 1000 women; only absences due to sickness

[128] *Absenteeism: Realities and Remedies.* Natl. Assoc. Mfrs., 1945.

and nonindustrial injuries disabling for eight consecutive days or longer were considered. The average number of persons employed by these companies was about 50,000 men and 2000 women.[129]

The relationship of the human aspects of industrial organization to absenteeism and management's opportunity to attack the problem from this angle has been pointed out by Fox and Scott.[130] They studied simultaneously the rates and trends of absences in the casting shops of three companies of comparable size and location. The major differences between Company A, which had a high rate of absenteeism and Company C, characterized by a low rate of absenteeism, were in the "internal

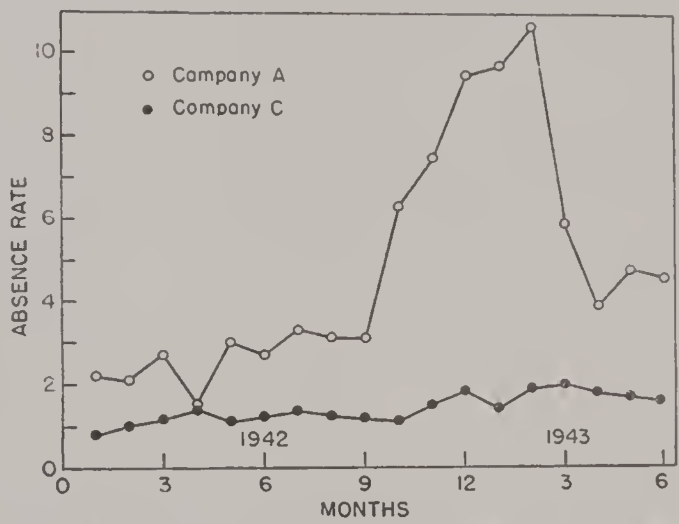


FIG. 20. Absence of workers in casting shops of two companies.[130] Absence rates were computed as percentages of workers on the payroll.

organization" of the two shops. In Company C an efficient two-way communication existed between the management and the workers: there was provision for the communication of workers' complaints upwards; also, company's policies and practices were explained to workers by their supervisors and foremen. The handling of the human relationships by the foreman was considered an important part of his job, and care was taken not to overburden him with technical responsibilities for production. One of the important factors directly tending to affect absenteeism was the difference in the payment system. Company A used individual piece-work payment and paid each caster for metal poured on one shift. Company C had a group payment system under which all the men *on all three shifts* on each furnace line were considered as a single payment unit. "These developments of internal organization have given rise to a team spirit, and have induced a social pressure of the team upon the individual of a kind that management would never dare to exercise."[130]

The rate of absences in the two companies for 18 months is represented in

[129] W. M. Gafafer, in *More Manpower Through Reduction of Absences.* Industrial Hygiene Foundation, 1942.

[130] J. B. Fox and J. F. Scott, *Absenteeism: Management's Problem.* Harvard Univ. Press. Cambridge, Mass., 1943.

Figure 20. In these data a series of consecutive days of absence by one man was counted as one absence. The rate of absences in Company C was lower than that of Company A throughout the period studied, and the fluctuations were negligible. In Company A there was a sharp rise in the absence rate during the winter months of 1942–43. This was a period of uncertainty and rapid changes of the work schedules and rates of payment. These factors were affecting both companies, but Company C was able to adjust to these changes by timely communications of the relevant information to the workers without creating confusion.

V. Comment

In dealing with production materials, management seeks the expert advice of test laboratories. When dealing with the human factor arbitrary decisions and rule-of-thumb are often used, even in cases where an experimental evaluation of possible alternatives is feasible. Thus it may be company's "policy" to enforce standing of the workers when the job could be done more comfortably and efficiently in the sitting position or when alternating between standing and sitting would be least fatiguing.

The concept of "scientific management" includes logically the human aspects of industrial efficiency. Contrary to the widely held opinion, F. W. Taylor was aware of the necessity for paying attention to the psychological aspects of management. In describing his experiment on increasing the productivity of the pig-iron handlers, he wrote: "It was our duty to see that this work was done without bringing on a strike among the men, without any quarrel with the men, and to see that the men were happier and better contented when loading at a new rate of 47 tons than they were when loading at the old rate of 12½ tons."[131] It is unfortunate that in the practice of time studies the regard for the human side of industrial efficiency has often been lost. Although the timing of the motion cycles is carried out by the mechanical engineer with great accuracy, the estimation of "normal" production rates and of "fatigue allowances" has little support in fundamental studies of sustained performance capacity in different types of industrial operations. The problem as to what constitutes a proper day's work is much more "bargained" about than objectively and dispassionately studied.

The determination of the most efficient work methods must involve consideration of physiological characteristics of the working human organism as well as individual-psychological and social-psychological factors. The human aspects of industrial efficiency represent a complex problem and its study along any single dimension alone is not sound.

Let us consider the problem of posture, as an example. We can study the effect of posture at work in terms of output, both as daily totals and as hourly output curves. We can determine the effect of the variations in posture on the subjective feelings of fatigue. The difference between doing work while sitting in a chair provided with a well-fitting back support and working in bended position, in which "static work" is done by continued contraction of the muscles counteracting the

[131] F. W. Taylor, *Principles of Scientific Management*. Harper, New York, 1913.

force of gravity, will be reflected as a difference in energy consumption. The increment in metabolism indicates the magnitude of this component of the total organic work cost. Sometimes the difference between two postures may be slight in terms of energy expenditure yet there may be a pronounced difference in the physiological effects. Thus, standing increases the basal energy expenditure only by 10 to 20 per cent, but the strain on circulation may interfere with work performance and health. It is interesting to note that a prolonged maintenance of a given posture may facilitate also the onset of "visual fatigue," measured as decreased ability to perceive differences in light intensity.[132]

The human organism, its interaction with the environment, and the interaction of various processes within the body represent a system of relationships that is very complicated but still amenable to scientific investigation and analysis. We share Jenkins' conviction that, in the studies of the human factor in industry as in the fundamental biological sciences, generalizations of known dependability can be obtained only by methods of *controlled observations*, involving the use of experimental and statistical analysis.[133] Only in this way can one distinguish between statements of industrial lore and scientific conclusions.

The impatience of the "practical man" with the inadequacy of the present-day methods and slow progress in dealing with such problems as selection of manpower is understandable, but the solution lies not in reverting to the techniques of palmists, phrenologists, and other pseudo-specialists on "human nature" but in supporting sound fundamental and applied research. Thus, in the task of predicting occupational adjustment, the only really practical approach, in the long run, is scientific development of more accurate and more refined techniques for the identification and evaluation of factors predictive of successful vocational adjustment.[134] Problems of reduction of fatigue and of long-term maintenance of an efficient labor force also demand scientific study.

In a large number of instances the available evidence can be used as a basis for taking practical steps leading to increased productivity, adjustment, and health of the worker. On the other hand, in some areas the information is incomplete. A number of important questions remain unanswered, partly because of inadequate research facilities. There is a need for bridging the gap between the laboratory approach to fitness and performance capacity on one hand and the raw, uncontrolled industrial situation. Also, the problems of the science of human work must be studied in a multi-variable context and by means of an interdisciplinary approach. The study of some important topics of industrial hygiene, such as effects of the mode of life—for example, of the amount and intensity of physical work—on "fitness," will require a completely new approach and research institutions equipped to carry on comprehensive studies on the adult man, extending over years and possibly decades.

[132] R. A. McFarland, A. H. Halway, and L. M. Hurvich, *Studies of Visual Fatigue*. Harvard Univ. Press, Cambridge, Mass., 1942.

[133] J. G. Jenkins, *Psychology in Business and Industry*. Wiley, New York, 1935.

[134] Paul Horst *et al.*, *Soc. Sci. Res. Council Bull.* No. 48 (1941).

Chapter Five

Environmental Factors in Fatigue and Competence

W. N. WITHERIDGE

Fatigue has been defined from the viewpoint of industry as "the sum of the results of activity which show themselves in diminished capacity for work." Sayers concluded in a review of the literature on major studies of fatigue that "Environmental conditions and relations with management and fellow workers are more important factors in fatigue than physical activity except in the 'heavy' industries that require hard physical labor."[1]

Unsanitary, uncomfortable, irritating, or annoying work environments can be avoided by proper organization and construction. Since fatigue and diminished capacity for work are correlated, the justification for capital and operating expenditures to prevent physically or mentally tiresome working conditions can be either humanitarian, economic, or both, depending on one's viewpoint. Progressive management is designing new plants and reconstructing old ones with a conviction that human satisfaction in the work environment will be an asset as marketable as the "good will" of the public.

Cushing[2], a representative of top management, supports this contention:

> "In the past, the success of a company has been judged largely by its financial statement. The question of human values, human relations, within the organization was considered as relatively unimportant, and even classified under the heading of 'sentiment.' However, it is now recognized that the financial statement is definitely affected by plant morale—that economic factors are definitely influenced by human factors. It is generally admitted by the more progressive companies that plant morale is as tangible and significant as production costs and machine maintenance."

The *environmental engineer* must realize the interdependence of mind and muscle in occupational fatigue, because it will help him avoid the pitfalls of de-

[1] R. R. Sayers, *War Med.*, **2**, 786 (1942).

[2] J. C. Cushing, in *Human Behaviour and Its Relation to Industry.* McGill Univ., Montreal, 1944.

signing or planning environmental conditions as though the worker were nothing more than a self-propelled bundle of mechanical energy. "With the concept of the human being as a totality of integrated physiologic functions, it is not possible to discuss gross muscle physiology separate from the physiology of the nervous system, the cardiovascular system, the respiratory system and other systems of the body."[3]

Man has been compared with machines and horses to determine the industrial cost of human energy. The conclusion, based on the premise that a man would generate all available foot-pounds of energy with reasonable exertion—that is, he would be willing to work—is that human energy is about 200 times as costly as machine power, and about 20 times as costly as horsepower.[4] Mechanization minimizes human power, and the engineer who designs safe and comfortable industrial environments today does not attempt to justify his efforts on the basis of increased human foot-pounds of work, except in those jobs where physical labor predominates.

Mental efficiency is now much more important to industry than muscular efficiency. Yet we know, at present, a great deal more about the *methods* of preventing unsatisfactory work environments than we know about the economic savings that can be credited to desirable working conditions. Those managements and companies that foresee the value of attractive working conditions will make it possible to provide the more skeptical executives with the evidence they need to justify similar investments in human efficiency. Laboratory studies of working efficiency may be subjected to a certain amount of proper skepticism by the operating executive. Even field tests are easily misinterpreted because of the difficulty of testing the capacity of human beings without their knowledge. Consequently, proof of the economic advantages of good working conditions is the product of years of experience and careful cost accounting.

The subjects comprising this chapter will be divided as follows: (*1*) air conditioning, (*2*) light conditioning, (*3*) sound conditioning, and (*4*) sanitary conditioning. All of these combine to form the nucleus of the activity here termed *environmental engineering*. Equally important is the "safety conditioning" of the environment, but accident prevention is beyond the scope of the present discussion.

Safety engineering to some individuals is synonymous with environmental engineering, as is likewise the comprehensive profession of *sanitary engineering*. *Industrial hygiene engineering* and *public health engineering* frequently imply the control of all factors important in the human environment, but they cannot be used without suggesting a specialized viewpoint. *Architectural engineering* possibly comes near the concept of environmental engineering to be used in this chapter, although it is usually more concerned with the design of structures for human

[3] V. K. Harvey and E. P. Luongo, *Occupational Med.*, *1*, 1 (1946).

[4] R. T. Dana, *The Human Machine in Industry*. Codex Book Co., New York, 1927. pp. 1–23 and 85–124.

satisfaction than with the creation and operation of safe, sanitary, and satisfactory processes within these structures.

The environment in this discussion is limited to places of employment, generally within buildings. It does not encompass the entire field of environment control, including community sanitation, public utilities, transportation, and city planning, which is often implied by the designation of *civil engineering*.

I. Air Conditioning

Complete air conditioning includes the control of temperature, humidity, radiation, air movement or drafts, and cleanliness or purity of the air. The control of air cleanliness or air quality is generally a matter of ventilation or air cleaning. Since this subject is covered in Chapter Ten, only the thermal aspects of air conditioning are discussed here.

A. COMFORT AND EFFICIENCY

Thermal comfort in the environment is the primary purpose of air conditioning. All persons have experienced the rapid loss of interest in *mental* work at elevated temperatures and humidities; *physical* work at high temperatures is not impossible, if the mind is willing. Although most persons would admit the existence of a good correlation between thermal comfort and mental activity, it is not easy to demonstrate a loss of physiological or psychological efficiency under the influence of conditions slightly above or below the "comfort zone." In fact, recent experiments on work efficiency indicate that special incentives may overcome the effects of a most uncomfortable environment (see also Chapter Four).

The literature contains reports of experiments that demonstrate either increased or decreased productivity in the presence of slightly uncomfortable air conditions. None of these experiments has succeeded in completely separating the psychological and physiological effects of the environment. Therefore, the air-conditioning engineer should not attempt to justify his expenditures for "comfort" air conditioning on the basis of *physiological* efficiency, because the results are highly unpredictable. Wartime experience proved that some of the most "ideal" combinations of temperature, humidity, and air motion resulted in widespread complaints of monotony, indicating the complex psychological aspects of air conditioning.

B. PHYSIOLOGICAL RESPONSES

A great deal of field and laboratory work has been done in recent years on the physiological responses of the body to its thermal environment.[5-12] In fact,

[5] F. C. Houghten, *Trans. ASHVE*, **50**, 87 (1944).

[6] (Physiological knowledge and ventilation practice), *Trans. ASHVE*, **45**, 111 (1939).

[7] (Physiological influence of atmospheric humidity), *Trans. ASHVE*, **48**, 317 (1942).

[8] C.-E. A. Winslow, L. P. Herrington, and A. P. Gagge (human body and environmental temperatures), *Am. J. Physiol.*, **120**, 1 (1937).

[9] C.-E. A. Winslow, L. P. Herrington, and A. P. Gagge (human body and atmospheric humidities), *Am. J. Physiol.*, **120**, 288 (1937).

Houghten, director of the Research Laboratory of the American Society of Heating and Ventilating Engineers for many years, indicated that the controversies on this subject at the beginning of the twentieth century were largely responsible for the organization of the Society's Research Laboratory.

Our knowledge of the physiological effects of the environment is still far from complete, especially in view of the rapid developments in methods of radiant heating. The reader is advised to follow the physiological summaries prepared for the *Annual Guide* of the ASHVE for the most recent reports and conclusions in this field.

One of the useful results of this physiological research is the *effective temperature* and its correlated *comfort chart* discussed in the next section. Other results are the application of fever therapy and refrigeration to the treatment of disease and traumatic injuries.[13,14]

C. EFFECTIVE TEMPERATURE INDEX

For approximately two decades the air-conditioning engineer in this country has designed his systems with some attention to the effective temperature he creates. This index of comfort combines the factors of temperature, humidity, and air motion, and excludes the effect of radiation to or from surfaces that have temperatures different from the dry-bulb temperature of the air. The numerical value of the index for a given atmosphere is the temperature of still and saturated air that gives an "identical" sensation of warmth.

The effective temperature index, or "warmth index," was developed by experimentation with human subjects under many combinations of temperature, humidity, and air motion to determine the boundaries of an arbitrary "comfort zone."[15] Figure 1 gives the results for very low velocity or "still air" conditions. Figure 2 is a nomographic chart incorporating air movements up to 700 linear feet per minute for persons wearing customary clothing. Figure 3 is a similar chart for persons stripped to the waist, demonstrating the greater sensitivity to air currents when a large surface of the skin is exposed.

It is now recognized that more study is necessary to permit satisfactory adjustment of the effective temperature in the presence of substantial positive or

[10] C.-E. A. Winslow, A. P. Gagge, and L. P. Herrington (air movement and heat losses from clothed human body), *Am. J. Physiol.*, **127**, 505 (1939).

[11] C. P. Yaglou (thermal index of atmospheric conditions and application to sedentary and industrial life), *J. Ind. Hyg. Toxicol.*, **8**, 5 (1926).

[12] W. J. McConnell and M. Spiegelman, *Trans. ASHVE*, **46**, 291 (1940).

[13] *ASHVE Guide*, 1946, Chap. 13.

[14] C. P. Yaglou, "Hospital Air Conditioning," in *The Environment and Its Effect upon Man*. Harvard School of Public Health, Boston, 1937.

[15] C. P. Yaglou, W. H. Carrier, E. V. Hill, F. C. Houghten and J. H. Walker, *Trans ASHVE*, **38**, 410 (1932).

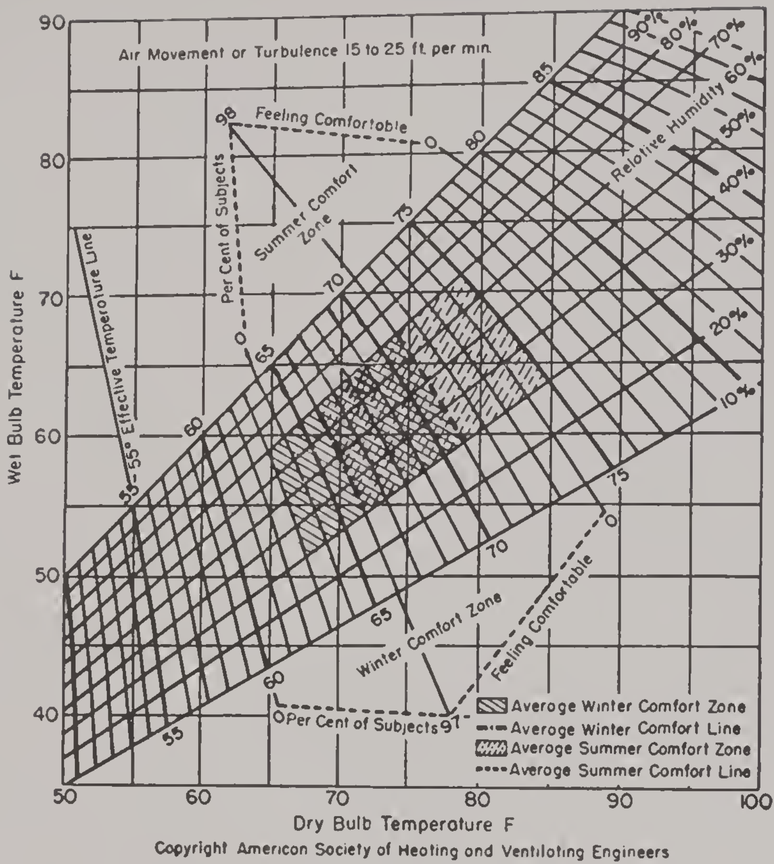


FIG. 1. Comfort chart for still air (*courtesy ASHVE*).[18] Both summer and winter comfort zones apply to the inhabitants of the United States only. Application of winter comfort line is further limited to rooms heated by central station systems of the convection type. The line does not apply to rooms heated by radiant methods. Application of summer comfort line is limited to homes, offices and the like, where the occupants become fully adapted to the artificial air conditions. The line does not apply to theaters, department stores, and the like where the exposure is less than 3 hours. The optimum summer comfort line shown pertains to . . . the northern portion of the United States and Southern Canada, and elevations not in excess of 1000 feet above sea level. An increase of one degree in effective temperature should be made approximately per five degrees reduction in north latitude.

negative radiation between the body and its environment.[16] The probability of extended use of radiant heating may bring forth a new index of thermal comfort combining temperature, humidity, air movement, and radiation. At present, the effective temperature and the mean radiant temperature are used as separate indices of the thermal character of the environment.[17] *Operative temperature* was recently introduced as a measure of the combined effect of air and room-surface

[16] F. C. Houghten, *Trans. ASHVE*, **50**, 87 (1944).

[17] C. M. Humphreys, O. Imalis, and C. Gutberlet, *Heating, Piping, Air Conditioning*, **18**, 101 (Mar., 1946).

[18] *ASHVE Guide*, 1946, p. 230.

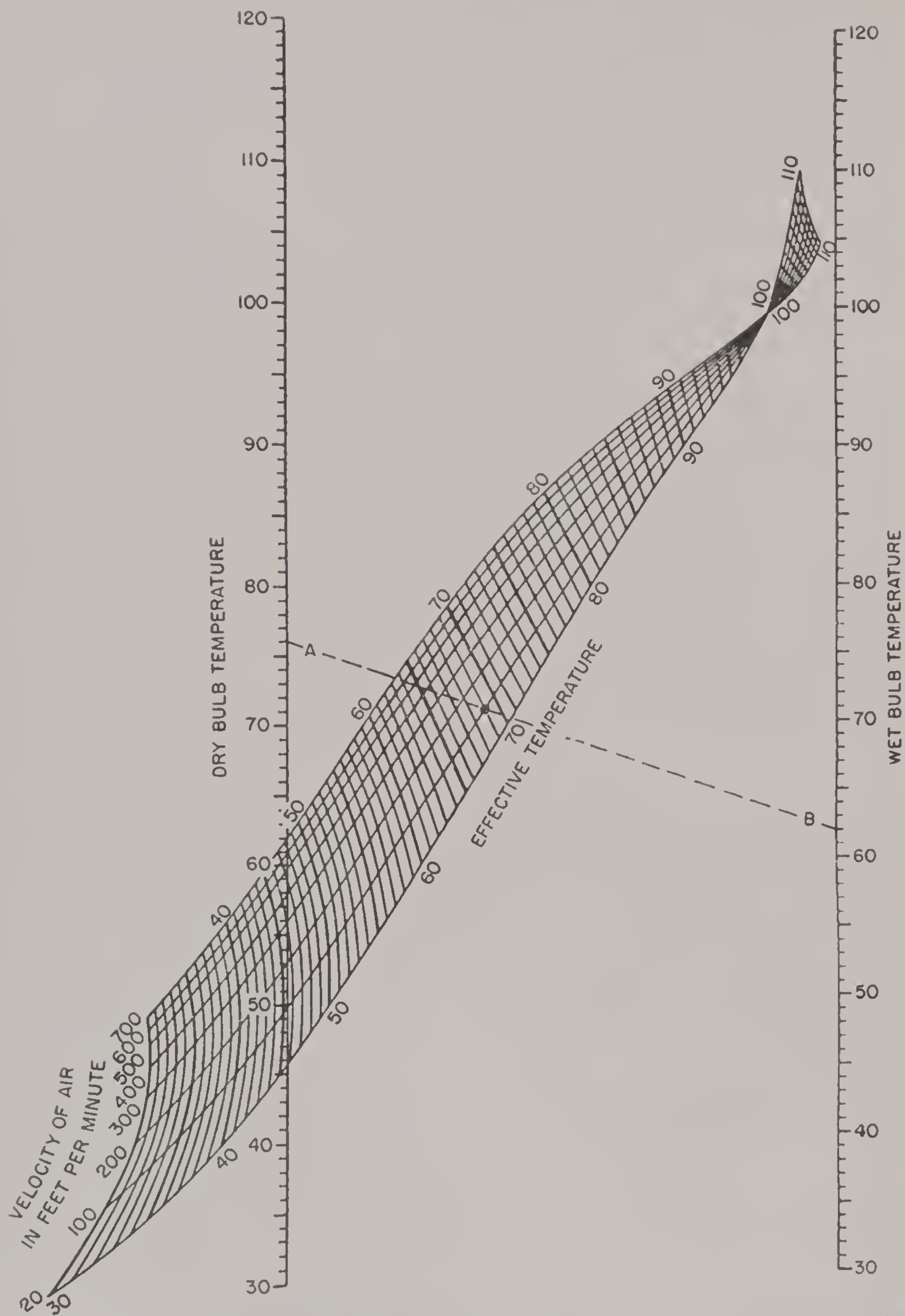


FIG. 2. *Normal scale* of effective temperature applicable to inhabitants of the United States wearing customary clothing, at rest or doing light physical work, and in rooms heated by convection methods (*courtesy ASHVE*).[16]

Example for Use of Figure 2. Given dry-bulb temperature of 76°, wet-bulb temperature of 62° and air velocity of 100 f.p.m., effective temperature will be 69° (refer to line *AB* on the chart).

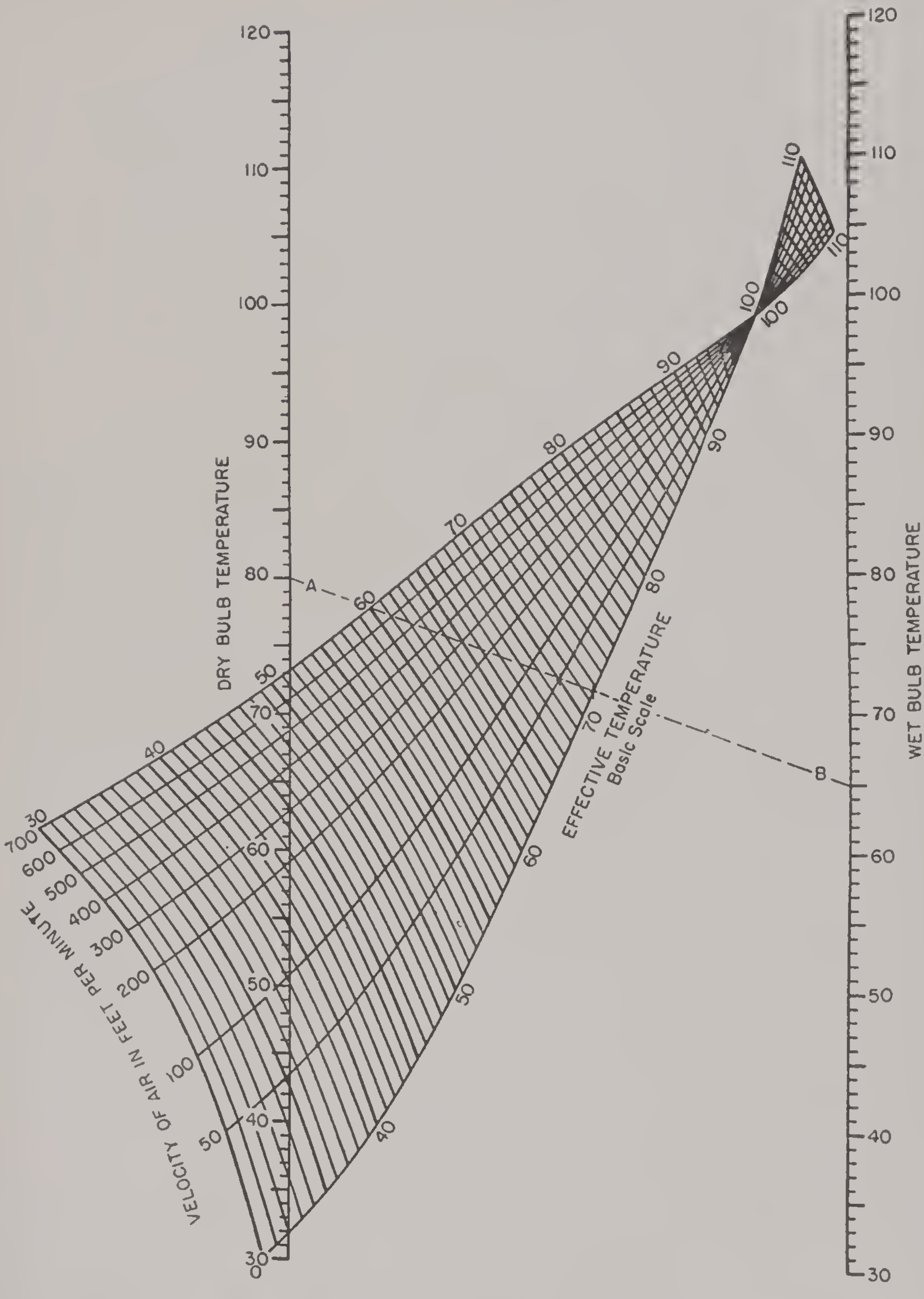


FIG. 3. *Basic scale* of effective temperature applicable to men stripped to the waist, at rest or doing light physical work in rooms heated by convection methods (*courtesy ASHVE*).[11]

temperatures,[19] but its use has not yet emerged from the laboratory into general engineering practice.

Bedford[20] derived a scale of *equivalent warmth* from a study of the comfort of industrial workers, which combines the effects of the four basic thermal factors. Its temperature range is limited, however, and also the comfort impressions of British workers are not identical with those of workers in this country.

British investigators have suggested that more comfortable and pleasant conditions may be obtained in the wintertime by keeping the mean radiant temperature of the surroundings high and the air temperature low, instead of maintaining the air and physical surroundings at substantially the same temperature. It is claimed that this more nearly approaches the invigorating freshness of a cool outdoor atmosphere combined with the radiant heat from the sun on a clear day.

D. TEMPERATURE DIFFERENTIALS IN HOT WEATHER

Early air-conditioning systems were unwisely operated on the basis that 70 to 75° F. was the best temperature range for human occupancy, regardless of the weather or the season. Theaters and public buildings, anxious to publicize the newly acquired air conditioning, subjected their clients and visitors to temperature shock, both going into and coming out of spaces 15 to 20° lower than outdoor temperatures. The mistake was soon discovered, but it demonstrated the surprising lack of understanding that man has of his thermal reactions to the environment. However, we dare not be too harsh with these early experiments on air conditioning, because research is still uncovering new "phenomena" in the automatic electrochemical controls of the temperature-sensitive nervous system.

Currently it is considered good practice to adjust the differential between indoor and outdoor temperatures according to the length of time spent in the cooler indoor space. Brief stays of less than a half-hour call for differentials in the neighborhood of 5°, while occupancy of several hours will permit greater differentials, perhaps 8 to 10° F. Thermostatic regulators are available to maintain a constant differential, or if desired a variable differential as outdoor weather changes. Furthermore, theaters and large buildings have found it practicable to acclimate the occupants entering or leaving by maintaining vestibules and lobbies at one or more temperature levels between indoor and outdoor conditions. In this way, larger total differentials are possible without sudden change or shock to the temperature balance of the body.

E. EXCESSIVE HEAT IN INDUSTRY

Skinner and Pierce[21] have prepared an interesting report on methods of overcoming the effects of excessive heat and humidity in industry. They are enumerated as follows: (*1*) use of salt, (*2*) air motion, (*3*) general exhaust ventilation,

[19] A. P. Gagge, in *Temperature—Its Measurement and Control in Science and Industry.* Reinhold, New York, 1941, p. 544.

[20] T. Bedford, *Ind. Health Research Board* (*London*), *Rept. No.* **76**, (1936).

[21] J. B. Skinner and W. M. Pierce, *J. Ind. Hyg. Toxicol.*, **27**, 31 (1945).

(*4*) local exhaust ventilation, (*5*) supplied air, (*6*) reduction of radiant heat, (*7*) enclosure of wet processes, (*8*) insulation, (*9*) adjustment of working hours, and (*10*) cooling of roof. The importance attributed to good air circulation is indicated by items 2, 3, 4 and 5.

Air-conditioned suits have been designed to give the worker a cool environment near a hot operation,[22] but they suffer from the inherent difficulties of all personal protective devices—restriction of activity, nuisance, and the worker's natural objection to confinement.

Most of the methods of combating excessive radiant heat are rather limited in their adaptability, and new plants are being designed with mechanization or isolation as the best means of preventing human exposure. Where workers cannot be located at a safe distance from intense radiant heat, they are shielded by stationary or movable screens of metal or asbestos, chain curtains, water curtains, or face masks with appropriate goggles or glass windows. Highly effective insulating panels have been available in recent years, and there is less reason today for permitting the double offense of heat waste and human exhaustion.

The upper limit of effective temperature for safety is in the range of 80 to 90° F. for men at work, depending on the amount of activity or heat generation.[23-28]

The consequence of heat stroke or heat exhaustion in workers exposed to excessive heat and humidity is well known. Most hot industries have studied their environments to determine methods for modifying such exposures. However, the mechanism of heat stroke is not limited to the hot industries. "Workers in cold trades are also susceptible to heat stroke on going out in the open in warm weather. An adjustment room should be provided to adapt them gradually to prevailing seasonal temperatures."[29]

F. LOSS OF SALT FROM THE BODY

A natural consequence of excessive perspiration is substantial loss of the body's salt content. The effects of such loss vary from lassitude and fatigue to heat cramps or prostration.

The hot industries have learned the value of supplying workers with salinized water or, more conveniently, salt tablets, usually the ten-grain size. Workers use from 5 to 10 such tablets per day depending on the severity of conditions or the amount of perspiration. Tablets may be either sodium chloride, sodium chloride

[22] F. C. Houghten, M. B. Ferderber, and C. Gutberlet, *Trans. ASHVE*, **47**, 403 (1941).
[23] F. C. Houghten, C. Gutberlet, and M. B. Ferderber, *Trans. ASHVE*, **49**, 188 (1943).
[24] M. B. Ferderber, F. C. Houghten, and W. L. Fleisher, *Trans. ASHVE*, **48**, 309 (1942).
[25] F. C. Houghten, A. A. Rosenberg, and M. B. Ferderber, *Trans. ASHVE*, **46**, 185 (1940)
[26] F. C. Houghten, M. B. Ferderber, and A. A. Rosenberg, *Ind. Med.*, **9**, 7 (1940).
[27] W. L. Fleisher, A. E. Stacey, Jr., F. C. Houghten, and M. B. Ferderber, *Trans. ASHVE* **45**, 106 (1939).
[28] C. P. Yaglou, *J. Ind. Hyg. Toxicol.*, **19**, 12 (1937).
[29] C. P. Yaglou, in *U.S. Dept. Labor Spec. Bull.*, No. **3** (1941).

and dextrose, or enteric-coated tablets for those who are unable to retain in their stomachs the quickly dissolving variety.

If salinized water is preferred, the concentration commonly used is about 1 tablespoonful of salt per gallon of water, which is nearly equivalent to the recommended salt concentration of 0.1 to 0.2 per cent.[30]

G. AIR-CONDITIONED CRANE CABS

Operators of crane cabs in some plants have recently enjoyed more comfortable and healthful atmospheres independent of the heat and smoke or other contaminants outside the cab. Air-conditioning and cleaning units are currently available handling from 200 to 2000 cubic feet of air per minute, and providing up to 50° differential between the operator's environment and air outside the cab. Apart from comfort, and air-borne disease prevention, the efficiency and alertness of crane operators is especially important for the safety of their fellow workers, and the conditioned cab was developed as a result of the demand for an economical, portable environment so that air conditioning of the entire building is unnecessary.

H. LOW TEMPERATURE

It is well known that hard work may generate enough body heat to make indoor temperatures as low as 50° F. quite comfortable. However, Yaglou[31] has suggested that 60° may be a desirable minimum "because of the possibility of chilling warm and perspiring body surfaces during rest periods."

Low temperatures appear to increase accident frequency by their effect on manual dexterity. Osborne and Vernon[32] demonstrated in British munition factories during World War I that the incidence of minor accidents reached a minimum at 67° F. and increased above and below this temperature. At 50° F. the accident frequency was about 35 per cent higher than at 67° F.

Within certain limits, the internal body temperature and the skin temperature can be controlled by suitable clothing properly worn. Wool is superior to cotton or linen; and, in the presence of high wind velocities outdoors or in low-temperature wind tunnels, the outer clothing should contain a windproof fabric, such as leather or rubber. Clothing should fit loosely in order to permit normal blood circulation to the extremities, and to provide an air space between the skin and clothing as additional thermal insulation. For intermittent exposures to low temperatures, clothing should be designed for convenient change, or workers will neglect its use.

Two new units have been proposed for the study of protective clothing, the "clo" and the "met." One "clo" is equal to the ordinary indoor clothing worn in cool weather, and is sufficient to keep a man comfortable at average room tem-

[30] Report of AMA Council on Pharmacy and Chemistry. *J. Am. Med. Assoc.*, **129**, 131 (1945).

[31] C. P. Yaglou, in *U.S. Dept. Labor Spec. Bull.*, No. 3 (1941).

perature while sitting in a chair. The amount of heat produced under these conditions is rated as one "met." If a man is working and producing 3 met, a 3-clo outfit will keep him comfortable at 40° F. If he is sleeping in a tent at 10° F., he would need a sleeping bag and clothing combination equal to 8 clo to prevent his body temperature from falling to dangerous levels.[32a]

I. HIGH AND LOW HUMIDITY

Moderation in atmospheric humidity has been one of the goals of environmental control for as long as man has understood the existence of air-borne water vapor. The physiological reasons behind man's preference for humidities in the range of 30 to 60 per cent are beginning to unfold, and recent experiments even suggest that the optimum humidity for human life may be near 70 per cent instead of the 50 per cent so often cited as the objective.[33]

Low humidity (10 to 20 per cent) tends to dry the mucous membranes of the upper respiratory tract as well as external body surfaces, and respiratory desiccation not only may be uncomfortable, but it also may lower the resistance to infection. Nevertheless, some persons make the general statement that indoor air should be "dry rather than damp," without specifying that this is preferably a summertime objective. During the heating season, persons suffering upper respiratory affections characterized by excessive dryness of the tissues do not agree that air should be dry rather than damp. Even so, many structures will not tolerate humidities above 35 per cent during the heating season because of the condensation of water on exterior walls and windows. Consequently, the desire for humid rather than dry air necessitates insulated wall construction and double or triple window glass.

High humidity is undesirable in the summer because it reduces the "drying power" of air moving across the body. Some hot weather air-conditioning systems have been designed with substantial dehumidification and very little cooling, on the basis that the body is much less subject to shock by large humidity differentials than to shock by temperature differentials producing the same body heat dissipation.

High humidity in cold weather is uncomfortable outdoors because moisture reduces the insulating power of clothing. Nevertheless, this same air drawn indoors and heated will result in more comfortable conditions because of its initially higher water vapor content compared with cold air having low humidity.

J. AIR MOVEMENT AND DRAFTS

" . . . the term *draft* as applied to conditions of the atmosphere within an occupied space may be accepted as meaning any local sense of cooling of a portion of the body,—caused either by an excessive movement of air of normal

[32] E. E. Osborne and H. M. Vernon, *Ind. Fatigue Research Board (London), Rept.* No. **19**, H.M. Stationery Office, 1922.

[32a] *Heating, Piping, Air Conditioning*, **18**, 71 (Oct., 1946).

[33] C.-E. A. Winslow, L. P. Herrington, and J. H. Nelbach, *Am. J. Hyg.*, **35**, 27 (1942).

temperature, by air having a normal velocity but a lower temperature, by excessive radiation to a cold surface, or any combination of these three effects."[34]

In view of these complex implications of the word *draft*, it is no wonder that great differences exist in the numerical values reported as the maximum tolerable air velocities in workplaces. In the case of a draft caused by air movement, the velocity of air that constitutes the draft depends on the season of the year, the physiological condition of the person, his activity, type of clothing, and the temperature difference between ambient and moving air.

Sedentary workers have complained of drafts when the air movement measured a few feet from the floor by a thermal anemometer is 30 to 40 l.f.m. (linear feet per minute) in the heating season, and 40 to 50 in the summer with cooled air. The objectionable air movement in summer with no air cooling is in the range of 100 to 200 l.f.m. for normal individuals.

Older persons are notably more sensitive to moderate air currents, and this fact should be considered when locating the workers in a large department that either cannot or should not be provided with uniform conditions. In fact, it must be recognized that workers are not standardized heat engines generating 400 or 600 B.t.u. per hour, and they have legitimate needs for an environment that can be modified somewhat according to metabolism and activity. This requires co-ordination of the work of the air-conditioning engineer, the plant medical department, and the supervisory personnel.

In summer near hot operations, air velocities as high as 500 l.f.m. have been observed without creating complaint or irritating draft. Such velocities, however, cannot be applied over a wide area, but instead are used as localized winds through which the individual may pass as often as he desires. Workers at fixed stations should not be subjected to constant or continuous air velocities above 200 l.f.m. If cooled or refrigerated air is passed over the working zone, the air velocity for comfort may be as high as 100 l.f.m. with small temperature differentials.

"Still air" in residential and commercial comfort air conditioning has for years been assumed to fall in the range of 15 to 25 l.f.m. These same values in a machine shop are denounced as "stagnant," and for many industrial environments 50 l.f.m. is properly rated as still air.

Somewhat akin to drafts are the high-temperature air blasts coming from heating systems with their discharge grilles located too near the occupied zone. So far, no generally accepted schedule of air movement combined with maximum permissible temperatures in the occupied zone has been produced.

K. ACCLIMATIZATION IN AIR CONDITIONING

Acclimatization is the term used to signify the gradual shift in the body's thermal response to its environment so that its heat balance can be maintained under a new combination of atmospheric conditions. Acclimatization accounts

[34] F. C. Houghten, C. Gutberlet, and E. Witkowski, *Trans. ASHVE*, **44**, 289 (1938).

for the difference between the winter and summer comfort lines shown on Figure 1, namely 66° and 71° effective temperature.

"According to the best information available from the Society's [ASHVE] Laboratory and other studies, acclimatization requires from one to two weeks. A longer period is indicated for acclimatization to cold than is required for acclimatization to heat. The Laboratory has found from seven to ten days required for acclimatization to heat, either as a result of change in summer weather or for men working in a hot environment."[35]

Carrier[36] cites an interesting example of the easily overlooked world-wide variations in acclimatization:

" . . . workers in tropical and semi-tropical countries such as India, for example, require temperatures above 80°. An illustration of this was found in the first air-conditioning plant installed in an Indian cotton mill. It was started up during the monsoon season when the outside temperature was 105° and the air was very dry. The mill temperatures to which the Indian workers were accustomed ran as high as 110° and 115°. The engineer in charge was greatly delighted when on a 105° day outside he maintained a temperature of 80° with 80 per cent relative humidity inside the mill, but the Indian operatives refused to work in so cold an atmosphere and he was obliged to provide a means for heating his spray water."

L. PSYCHOLOGY OF AIR CONDITIONING

Some of the plants built during World War II covered tremendous floor area between solid walls to conform with black-out design requirements. They were generally well air conditioned, but sometimes were provided with so nearly uniform distribution of air that the occupants did not believe there was any ventilation or air replenishment. This, coupled with the fact that no windows were available to establish visible communication between indoor and outdoor atmospheres, led to persistent complaints that inside air was stale, stagnant, stuffy, suffocating, or simply bad. Invariably the only permanent solutions to these complaints were based on a realistic knowledge of the layman's methods of appraising his atmospheric environment: (*1*) an audible (but not too noisy) and visible circulating fan; (*2*) ribbon streamers attached to air-supply grilles; (*3*) variable rather than smooth or uniform air currents; (*4*) clear glass windows or transparent glass blocks to display the weather; (*5*) ventilating ducts obviously piercing an outside wall; (*6*) moderately fluctuating rather than precisely constant temperature; and many other devices conceived to demonstrate to the occupant that something is really happening to his atmospheric environment to keep it constantly replenished. Some of these solutions are disappointing to the engineer whose goal is technical perfection in meeting a fixed combination of environmental conditions. But environmental engineering does not specify monotony as a desirable or even permissible objective.

M. AIR-CONDITIONING COMPLAINTS

A significant development of medical and physiological research is the increasing number of theoretical justifications or explanations for the complaints

[35] F. C. Houghten, *Trans. ASHVE*, **50**, 87 (1944).
[36] W. H. Carrier, *Ind. Med.*, **7**, 563 (1938).

of occupants that have been registered from the very beginning of mechanical control of indoor weather. Prior to such control, the individual's complaints had to be met by a change in dress, movement toward or away from hot or cold surfaces, opening or closing of windows or doors, more fuel on the fire or a trip to the icebox, and many similar acts for which the individual accepted personal responsibility. But now, to most persons, air conditioning is a promise to take over complete responsibility for their atmospheric comfort, and their complaints therefore become a matter of public and engineering concern.

Consequently, the environmental engineer now realizes that he must spend less time devising technical refutations for complaints, and devote more of his time to the study and design of psychological as well as physical methods of overcoming sincere and genuine objections to the thermal environment.

X. MEASUREMENT OF AIR CONDITIONS

The desire for a single instrument to measure the combined effect of temperature, humidity, radiation, and air movement has led to a number of devices with widely different characteristics. None has succeeded in capturing the honor position as a convenient and reliable stand-in for the human being, for it appears from experiences with instruments already conceived that such an objective fails to appreciate the complexity of thermal physiology. In fact, we do not yet know all the facts about the body's thermoregulatory processes, and for this reason alone an instrument for predicting the effect of a given environment on human beings is certain to be incomplete. Furthermore, the variability and range of human sensation cannot be studied and reported reliably with an instrument that buries all the four basic factors in a single numerical index. The human brain reports many different reactions from many parts of the body and accordingly it is not an integrator but rather an analyzer of the thermal environment. Thus, the same person may be both comfortable and uncomfortable when the sensations from the neck and feet are due to widely different temperature and air-movement combinations.

It is therefore good practice at the present time to determine individually the air temperature with a shielded dry-bulb thermometer or sensitive thermocouple, humidity indirectly with a wet-bulb thermometer, air movement with any of the reliable low-velocity anemometers (Chapter Ten), and the mean radiant temperature computed from readings of an unheated black globe thermometer.[37-39]

Those who wish to study the characteristics of heated instruments that have been used to combine two or more of the four thermal factors are referred to a

[37] A. P. Gagge, in *Temperature—Its Measurement and Control in Science and Industry* Reinhold, New York, 1941, p. 544.

[38] T. Bedford and C. G. Warner, *J. Hyg.*, **34**, 458 (1934).

[39] H. M. Vernon, *J. Ind. Hyg. Toxicol.*, **19**, 498 (1937).

review by McCord and Witheridge[40] and to original papers on the *eupatheoscope*,[41] *coolometer*,[42] *thermointegrator*,[43] *and heated globe thermometer*.[44]

II. Light Conditioning

Architectural, illuminating, and heating and ventilating engineers know that the thermal and visual conditioning of occupied spaces should be a co-operative project. Those who buy or occupy buildings for residential, commercial, or industrial purposes also would like well-integrated structures, but in practice they seldom appreciate the implications of air and light integration.[45–49]

In the nineteenth century it was well known that ventilation was required to remove the heat and products of combustion from oil or gas illumination. Today it is not so generally understood that some industrial buildings may have enough internal heat created by electric illumination to require air cooling rather than heating except in the most severe winter weather. Hot or cold cathode fluorescent lights may reduce the cooling load somewhat unless the same amount of electrical energy is used to provide substantially higher levels of illumination than was customary with incandescent filament lamps.

The fenestration of industrial structures is a combined lighting and ventilating problem—so much so that designers of translucent or transparent glass-block wall construction have been forced in many cases to pierce their light and heat transparent walls with movable window sections of conventional design to satisfy human psychological and thermal desires. Recent attention to building orientation and wall design to exclude the summer sun and admit the winter sun emphasizes the intimate relation between lighting and indoor temperature control. The development of double and triple air-glass window panes is a concession to the fact that human beings do not like to be confined behind opaque, well-insulated walls no matter how economical of heat they may be. The use of exterior horizontal and vertical sunlight baffles on the skyscrapers of Brazil is an example of coordination with the air-cooling equipment.

The environmental engineer, whatever he may be called in various organizations, is an engineering co-ordinator in a real sense because of his special interest in compatible requirements of air conditioning, lighting, sound control, safety, and sanitation. He must try to anticipate and reconcile the objections of human beings

[40] C. P. McCord and W. N. Witheridge, *J. Am. Med. Assoc.*, *111*, 1647 (1938).
[41] A. F. Dufton, *Building Research Board (London)*, *Tech. Paper* No. *13* (1932).
[42] W. S. Weeks, *J. Ind. Hyg. Toxicol.*, *13*, 261 (1931).
[43] C.-E. A. Winslow and L. Greenburg, *Heating, Piping, Air Conditioning*, **7**, 41 (Jan., 1935).
[44] C. P. Yaglou, *J. Ind. Hyg. Toxicol.*, **17**, 185 (1935).
[45] H. M. Sharp, *Heating & Ventilating*, Reference Section No. **7**, *39*, 36 (Nov., 1942).
[45a] *Eng. News Record*, *136*, 784 (1946).
[46] H. Blumenfeld, *Architectural Record*, *88*, 49 (Dec., 1940); *89*, 69 (April, 1941).
[47] W. Sturrock, *Trans. ASHVE*, *44*, 213 (1938).
[48] W. G. Darley, *Trans. ASHVE*, *46*, 367 (1940).
[49] M. Luckiesh and A. H. Taylor, *Gen. Elec. Rev.*, *43*, 410 (1940).

to new methods of construction and manufacturing, so that it does not become necessary to perpetuate the condition aptly described by an eminent contemporary statesman: "We shape our buildings, then our buildings shape our lives!" Accordingly, it is important to remember during the following discussion of natural and artificial illumination that the standards of performance in some cases may have to be compromised with the standards of natural and artificial ventilation. This is a problem of engineering judgment that cannot be reduced to words for all types of buildings. It is also a problem of determining the point at which natural illumination and ventilation must give way to partial or complete mechanical control of indoor lighting, heating, cooling, and other conditions.

A. REQUIREMENTS FOR COMFORTABLE AND EFFICIENT SEEING

The illumination principles that promote safe, comfortable, and efficient visual performance apply whether daylight or artificial illumination is provided. It is therefore convenient to summarize them here before outlining the methods of obtaining good natural and electric light. For the purpose of this discussion it is assumed that the eyes are normal or have been optically corrected to enable them to take proper advantage of the visible environment.

Four fundamental factors determine the visibility of objects: brightness, contrast, size, and time available for seeing.

Brightness is the term used to indicate the amount of light energy that an object sends to the eye. It is the result of illumination intensity in foot-candles reaching the surface of the object, and the *diffuse reflection factor* of the surface. Highly polished surfaces are predominately specular reflectors and often create reflected glare. Specular reflection may either increase or decrease the contrast between object and background, and accordingly may either assist or impair the visibility of the object.

Reflection factors vary from practically zero to nearly 100 per cent.[50] Thus a surface with a diffuse reflection factor of 8 per cent needs 10 times the illumination in foot-candles required by a surface having an 80 per cent factor to create the same brightness effect on the eye. Brightness is usually expressed in *foot-lamberts* (ft.-L.), and is the product of the diffuse reflection factor (DRF) and the foot-candles (ft.-c.) of illumination:

$$\text{ft.-L.} = \text{DRF} \times \text{ft.-c.}$$

The brightness of light sources such as lighting equipment, sky, and clouds is commonly expressed in candles per square inch. On this scale the brightness of the sun is about 1,000,000; bare tungsten filaments, 1000 to 10,000; frosted tungsten-filament lamps, about 100; candle flames, about 10; and modern fluorescent lamps, from 3 to 6.

One candle per square inch equals 452 ft.-L., or, in the metric system, 487 millilamberts. The brightness and area of a light source determine its candle-

[50] M. Luckiesh, *Light, Vision and Seeing.* Van Nostrand, New York, 1944.

power. The intensity of direct glare from a light source varies directly with its candlepower and inversely with the square of its distance from the eyes. Even a low-brightness light source may be glaring if it covers a large area in the visual field. The effect of a glare source becomes less as the angular distance from the line of vision increases.

Contrast is composed of *brightness* contrast and *color* contrast. Brightness contrast is the difference in brightness of an object and its background expressed as a percentage of the higher brightness value. Thus, if the object is brighter than the background, the brightness contrast of the combination in per cent is:[51]

$$BC = 100 \times \frac{\text{brightness of object} - \text{brightness of background}}{\text{brightness of object}}$$

The brightness ratio between the immediate area of visual work and the surroundings must be kept within reason to avoid discomfort. This is especially important in the selection of supplementary lighting, for the brightness ratio between the work and its surroundings should not be more than 10 to 1, and for best visual performance should be less than 5 to 1. These ratios apply whether the surroundings are darker or lighter than the work area.

Color contrast may be superimposed on brightness contrast to improve the visual performance, even to the point of using light of controlled color to enhance the contrast.[52–57] The use of various colored paints to accent parts of machinery and to promote safety are applications of the principle of color contrast.

Size of the object, brightness, and brightness contrast are all interrelated in the determination of the threshold of visibility. Figure 4 combines these elements graphically. The threshold size is expressed as the angle subtended at the eye, usually in angular minutes in one dimension. This is necessary to eliminate the variable factor of distance as it affects the apparent size of the object. The threshold size for persons with normal vision and with good brightness contrast is about one minute. Figure 4 illustrates how important the brightness of

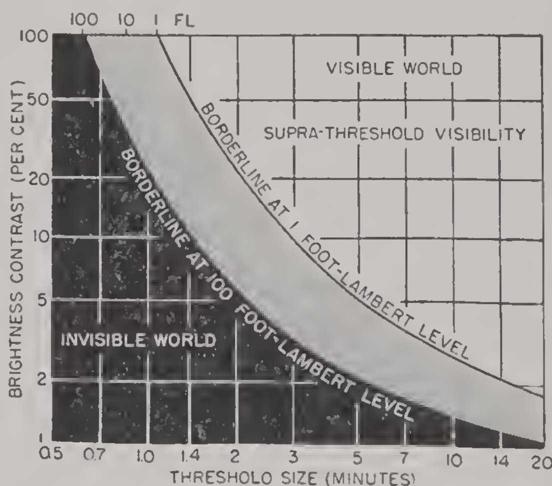


FIG. 4. Increase of "visible world" at expense of "invisible world" as brightness level increases. For a given case the brightness level increases as the foot-candle level increases.[50]

[51] M. Luckiesh, *Light, Vision and Seeing*. Van Nostrand, New York, 1944.
[52] M. Luckiesh. *Color and Colors*. Van Nostrand, New York, 1938.
[53] A. H. Taylor. *J. Optical Soc. Am.*. **32**, 651 (1942).
[54] D. Nickerson. *Illum. Eng.* **36**, 373 (1941).
[55] A. A. Brainerd and M. Denning. *Illum. Eng.*, **36**, 1397 (1941).
[56] F. Birren. *The Sight-Saving Review*, **13**, 3 (1943).
[57] *Ind. Health Bull., Division of Industrial Health (Ottawa, Canada)*, (Sept. 1946).

an object and its contrast with the background are to visual acuity. Visual acuity is proportional to the reciprocal of threshold size.

Time is important where speed of seeing is essential to good visual performance, as for industrial inspection, high-speed machine work, and accident prevention. The contrast between an object and its background has great influence on the time required for certainty of recognition. Likewise the illumination intensity in foot-candles has a direct effect on the time factor by its effect on surface brightness of the object. An increase from 1 to 100 ft.-c. approximately doubles or triples the speed of seeing.

In accordance with the fundamental law of physiological response that states that a sensation (vision) is proportional to the logarithm of the stimulus (brightness) it has been suggested that significant change or improvement in the effectiveness of seeing depends on geometric rather than arithmetic increments of illumination. Thus, the recommended foot-candles in Table 1 are arranged as a progressing scale in the order of 5, 10, 20, 50, and 100, representing rounded numbers with ratios of approximately 2.

TABLE 1

Recommended Illumination Levels[57a]

Number of foot-candles	To be used for
100 or more	Very severe and prolonged tasks, such as fine needlework, fine engraving, fine penwork, fine assembly, sewing on dark goods, and discrimination of fine details of low contrast, as in inspections.[a]
50 to 100	Severe and prolonged tasks, such as proofreading, drafting, difficult reading, watch repairing, fine machine work, average sewing, and other needlework.
20 to 50	Moderately critical and prolonged tasks, such as clerical work, ordinary reading, common benchwork, and average sewing and other needlework on light goods.
10 to 20	Moderate and prolonged tasks of office and factory, and when not prolonged, ordinary reading and sewing on light goods.
5 to 10	Visually controlled work in which seeing is important, but more or less interrupted or casual, and not involving discrimination of fine details or low contrast.
1 to 5	Inadequate for most critical seeing; satisfactory for perceiving larger objects and for casual or conversational seeing.

[a] Recent studies have indicated that eye fatigue may be experienced in some installations above 50 ft.-c.[57b]

A more comprehensive treatment of lighting requirements for industrial operations is given in the American Standards Association code on industrial lighting.[58] The following excerpt from this code summarizes the requirements of three grades of visual tasks:

"*Group A*. These seeing tasks involve (*a*) the discrimination of extremely fine detail un-

[57a] M. Luckiesh and F. K. Moss, *Trans. Illum. Eng. Soc. (N. Y.)* **29**, 661 (1934)

[57b] M. A. Tinker, *Am. J. Pub. Health*, **36**, 963 (1946).

[58] (Recommended industrial lighting), *ASA Code A-11-1942*. Sponsored by Illum. Eng. Soc. (N. Y.) (1942).

der conditions of (*b*) extremely poor contrast, (*c*) for long periods of time. To meet these requirements, illumination levels above 100 footcandles are recommended. To provide illumination of this order, a combination of at least 20 footcandles of general lighting plus specialized supplementary lighting is necessary. The design and installation of the combination systems must not only provide a sufficient amount of light but also must provide the proper direction of light, diffusion, eye protection, and insofar as possible must eliminate direct and reflected glare as well as objectionable shadows.

Group B. This group of visual tasks involves (*a*) the discrimination of fine detail under conditions of (*b*) a fair degree of contrast (*c*) for long periods of time. Illumination levels from 50 to 100 footcandles are required. To provide illumination of this order a combination of at least 20 footcandles of general lighting plus specialized supplementary lighting is necessary.

Group C. The seeing tasks of this group require the discrimination of fine detail by utilizing (*a*) the reflected image of a luminous area or (*b*) the transmitted light from a luminous area.

The essential requirements are (*1*) that the luminous area shall be large enough to cover the surface which is being inspected and (*2*) that the brightness be within the limits necessary to obtain comfortable contrast conditions. This involves the use of sources of large area and relatively low brightness in which the source brightness is the principal factor rather than the footcandles produced at a given point."

In 1942 a committee of the Illuminating Engineering Society canvassed a substantial cross section of American war industry to obtain field opinions on the practical values of improved lighting.[59] The reported benefits were summarized as follows: (*1*) accuracy of workmanship; (*2*) less spoilage; (*3*) faster seeing; (*4*) greater ease of seeing; (*5*) less eyestrain and fatigue; (*6*) better utilization of floor space; (*7*) greater ease of keeping plant clean; (*8*) improved labor conditions; (*9*) greater safety.

"The increases in production, decreases in spoilage and the reduction in the number of accidents, accompanying the introduction of higher levels of illumination in industrial plants, are accredited to better visual conditions. Under higher levels of illumination the eye has been shown to respond accordingly, by: (*1*) increased ability of perception; (*2*) increased speed of discrimination or rapidity with which the eye is able to identify a difference or differences in objects; (*3*) increased accommodation, or the ability of the eye to focus upon objects at different distances; (*4*) improvement in sustained vision, or the ability of the eye to keep a clear view of all details of an object under continuous observation; and (*5*) increased speed of vision or speed of reading . . ."[60]

An extensive literature is already available for further study of the psychology and physiology of seeing,[61–71] and a great deal of additional industrial data will undoubtedly emerge from the experience of World War II.

[59] *Illum. Eng.*, **38**, 13 (1943).

[60] W. Harrison and K. A. Staley, *Fundamentals of Illumination.* General Electric Company, Cleveland, 1931.

[61] M. Luckiesh, *Light and Work.* Van Nostrand, New York, 1924.

[62] M. Luckiesh and F. K. Moss, *The Science of Seeing.* 2nd ed., Van Nostrand, New York, 1938.

[63] M. Luckiesh and F. K. Moss, *Trans. Illum. Eng. Soc. (N. Y.)*, **31**, 655 (1936).

[64] W. Harrison and M. Luckiesh, *Illum. Eng.*, **36**, 1109 (1941).

[65] L. Resnick, *Eye Hazards in Industry.* Columbia Univ. Press, New York, 1941.

[66] L. R. White, R. H. Britten, J. E. Ives, and L. R. Thompson, *U.S. Pub. Health Bull.* No. **181** (1929).

B. NATURAL ILLUMINATION OR DAYLIGHTING

Although the cost of artificial light has been dropping steadily in recent years, there is no doubt that utilization of all possible natural light will save money in the lighting account. However, it is equally true that the cost of air cooling for buildings located near the equator may give the windowless or "blackout" plant an economic advantage over the generously glazed building. In northern climates, solar radiation may be used to reduce the heating load in the winter. It is therefore unwise to compute the relative costs of various lighting methods without anticipating the corresponding effects on the air-conditioning system.

The design of factory buildings to receive a given level of natural illumination is complicated by a number of variables that are either inevitable or controllable. Winter light is about 50 per cent less than summer light in the northern United States. Dust accumulation on exterior and interior glass surfaces may cut out 50 to 80 per cent of the light available immediately after window washing. Light varies hourly throughout the day. The movement of clouds creates a constantly changing illumination on some days. Weather variations create a range of outdoor daytime illumination from 10,000 down to 100 ft.-c., or lumens per square foot.

The prediction of daylighting intensities and distribution from the architectural design and fenestration of industrial buildings should be left to the illuminating engineer. Buildings can be designed for efficient utilization of natural light. Lighting requirements have exerted a growing influence on architectural design, and earlier standards of daylighting are certain to be revised to conform with current practices.

Special transparent and translucent materials are modifying the distribution characteristics of sun and sky illumination, so that new studies of light intensity variations throughout daylighted workrooms will be necessary. Roof, wall, monitor, and skylight contours have been redesigned for the modern factories to achieve more uniform daylight within. Therefore, daylighting standards based solely on the ratio of window area to floor area (such as 20 to 40 per cent) are quite inadequate for contemporary industrial architecture, and may even be so written into building codes as to hamper the sound development of better design for efficient daylighting.

Those who wish to study the technique of estimating and appraising the natural illumination of buildings of all types and proportions will find an extensive literature containing both mathematical and empirical procedures.[72-75]

[67] W. G. Darley, *Improving the Visibility of Industrial Tasks; Industrial Aspects of Ophthalmology.* Natl. Soc. for Prevention of Blindness, 1944, p. 83.

[68] E. W. Winkler, *Trans. Thirty-First Natl. Safety Congress*, **142**, 665 (1942).

[69] H. C. Weston, *Ind. Health Research Board (London), Rept.* No. **87**, H.M. Stationery Office, 1945.

[70] M. A. Tinker, *Am. J. Pub. Health*, **36**, 963 (1946).

[71] A. M. Culler, *J. Am. Med. Assoc.*, **116**, 1349 (1941).

[72] J. E. Ives, F. L. Knowles and L. R. Thompson, *U.S. Pub. Health Bull.* No. **218** (1935).

[73] H. H. Higbie and W. C. Randall, *Trans. Am. Soc. Mech. Engrs.*, **51**, 38 (1929).

[74] *Industrial Daylighting by the Fenestra Method.* Detroit Steel Products Co., 1929.

[75] G. M. Rapp and A. H. Baker, *Trans. Illum. Eng. Soc. (N. Y.)*, **36**, 1129 (1941).

C. ARTIFICIAL ILLUMINATION

Modern artificial illumination is much superior to daylighting from the standpoint of flexibility and precision of control. It makes possible providing strong light that may be adjusted in any direction to enhance contrast and minimize glare; avoidance of variations due to cloudy and stormy weather and seasonal change in the length of day; and elimination of glare and shadows cast by shifting rays of the sun. Photoelectric illumination control may be used to vary the amount of artificial light to offset daylight fluctuation. One of the most interesting developments emphasizing the versatility of artificial lighting is the use of near ultraviolet or "black light" together with penetrating fluorescent oils and powders for industrial inspection work. This combination seems to be especially good for highly polished metal parts where inspection with visible light would be difficult and tiring.[76]

When the quantity and quality of light for a given visual task have been decided in accordance with the principles of efficient and comfortable seeing outlined earlier, the lighting engineer proceeds to select and arrange the fixtures and lamps for the desired light intensity, color, distribution, and direction. He must co-ordinate the general and local lighting systems to acquire the right brightness contrasts in the field of vision. His ingenuity must not be hampered by standards and procedures formulated years ago when the principal method of lighting was the incandescent lamp in a reflector or the diffusing globe spotted at regular intervals throughout the workroom. The environmental engineer must be ready to modify his demands for the luminous environment to correspond with the latest improvements in electric lighting equipment; his job is principally that of studying and specifying illumination objectives and then carefully observing the physical installations developed by the illumination engineer to determine whether his requirements are reasonable and economical.

An appreciation of the technical problems confronting the industrial lighting engineer can be obtained by studying the many reports on requirements in various industries[77–84] and on the methods and equipment for general and supplementary lighting of manufacturing operations.[85–90]

[76] *Illum. Eng.*, **40**, 901 (1945).
[77] (Printing industry), *Trans. Illum. Eng. Soc.* (*N. Y.*), **31**, 277 (1936).
[78] (Textile industry), *Trans. Illum. Eng. Soc.* (*N. Y.*), **32**, 247 (1937).
[79] (Shoe manufacturing industry), *Trans. Illum. Eng. Soc.* (*N. Y.*), **32**, 289 (1937).
[80] (Candy manufacturing industry), *Trans. Illum. Eng. Soc.* (*N. Y.*), **32**, 483 (1937).
[81] (Cleaning and pressing industry), *Trans. Illum. Eng. Soc.* (*N. Y.*), **32**, 613 (1937).
[82] (Intricate production, assembly and inspection processes), *Trans. Illum. Eng. Soc.* (*N. Y.*), **32**, 1019 (1937).
[83] (Machining of small metal parts), *Trans. Illum. Eng. Soc.* (*N. Y.*), **34**, 21 (1939).
[84] (Power presses), *Trans. Illum. Eng. Soc.* (*N. Y.*), **34**, 153 (1939).
[85] *Lighting for Production in the Factory.* General Electric Co., Cleveland, 1939.
[86] M. Gauthier, *Architectural Record*, **92**, 63 (Sept. 1942).
[87] W. Harrison and C. E. Weitz, *Illumination Design Data.* General Electric Co., Cleveland, 1936.
[88] C. L. Amick, *Fluorescent Lighting Manual.* McGraw-Hill, New York, 1942.
[89] *Light from Floors (White Cement).* Universal Atlas Cement Co., Indiana, 1945.

The scarcity of maintenance labor during World War II resulted in concerted attention to the design and location of fixtures for easy servicing or replacement. A special pole was developed for fluorescent tubes so that replacement could be made quickly from the floor. Lampholders or sockets were improved to facilitate insertion and removal of the tubes. Fixtures have been designed and constructed of materials so that frequent washing with soap and water becomes practicable.

Architects are learning to place lighting fixtures so that servicing is less troublesome. Where high-ceiling installations are still necessary, ingenious automatic ladders and elevating towers are now available to take the maintenance men rapidly to the individual lighting fixtures. In some plants the fixtures have been installed on hangers that can be lowered to the floor for servicing. A tricycle ladder has been designed for a two-man service team and their equipment as a means of speeding the job of lighting maintenance for large buildings and long illuminated passageways. All these and other innovations now make it possible to maintain high-quality artificial light in the modern industrial plant.[91]

D. MEASUREMENT OF ILLUMINATION

The quantity of light reaching the visual field or visible object is measured and reported in foot-candles; it may also be given in lumens per square foot, since this unit is numerically equal to the foot-candle unit. The use of lumens per square foot has the advantage of a more obvious mathematical relation to the output of light sources in lumens or the expenditure of electrical energy in lumens per watt. Rational estimates of the size and distribution of light sources can thus be made from the surface area to be illuminated and the amount of light required in lumens per square foot. Light quantities also can be readily converted into watts per square foot for the benefit of air-conditioning engineers.

Convenient photoelectric illumination meters have been available for several years operating in the range of 1 to 50 or 1 to 500 ft.-c.[92] Special meters can be obtained with other calibrations and sensitivities where necessary. For very low illumination levels instruments are provided with multiple light-sensitive disks to generate measurable amounts of electric current. If a light meter is to be used for fluorescent or mercury vapor illumination as well as for incandescent light, special filter disks are applied over the light-sensitive cells to correct the fluorescent or mercury vapor emission spectrum to correspond with the quality of visible light from the incandescent filament lamp, or to correspond with daylight quality, whichever is the basis for calibration.

The lighting engineer also has at his disposal a portable visibility meter, designed by Luckiesh and Moss, by which he may estimate the relative difficulty

[90] E. S. Lincoln, *Industrial Electric Lamps and Lighting*. Essential Books, New York 1945.

[91] *Illum. Eng.*, *40*, 901 (1945).

[92] W. Harrison and K. A. Staley, *Fundamentals of Illumination*. General Electric Co., Cleveland, 1931.

of seeing tasks. Another instrument now available in a portable model is the brightness meter, which measures brightness values up to 75,000 ft.-L. A more elaborate instrument, designed by Luckiesh and Taylor, will measure brightness in the range of 0.002 ft.-L., the lowest value at which visual measurements are practicable, up to 50,000 ft.-L., the brightness of the bulb of a 100-watt inside-frosted tungsten lamp. This meter can be focused on distant objects and will measure the brightness of an object 1 foot wide at a distance of 500 feet.[93,94]

III. Sound Conditioning

The foregoing sections outlined the important features of the thermal and visual environment of human beings; this section adds another factor that merits integration with the whole environment.

Slocum,[95] in his pioneer treatise on noise and vibration engineering published in this country, concluded that: "The commerical value of pure air, effective lighting, and quiet surroundings in which mind and body can function normally, is now generally recognized by scientific management."

Because sound may be either air-borne or bone-conducted (transmitted to the skeleton through the structural members of the building), its control should be planned in advance of construction or before operation of manufacturing processes. Its control should be interlocked with other environmental controls by the teamwork of sound, light, heat, sanitary, structural, electrical, and production engineers.[96–99]

The windowless, artificially lighted bomber plant of World War II in some instances had walls packed with insulating material that retarded the passage of heat and was also credited with the reduction of excessive exterior noise. In windowed buildings, architects have found that one of the disadvantages of the single pane "picture window" extending across one side of a room is its transparency to air-borne sound. The use of double- or triple-window glazing not only conserves internal heat but also presents a greater barrier against outdoor noise. The sound-insulating effect of heavy concrete, brick, or masonry walls is well known, and their use at strategic points *within* the structure has been especially valuable in isolating office areas from noisy factory spaces. In fact, in the well-integrated structure a "fire wall" may also serve as a "sound wall."

A. EFFECT OF NOISE ON HUMAN BEINGS

It has been thoroughly demonstrated by field and laboratory work that industrial noise may produce effects ranging from mental inefficiency, nervousness,

[93] *Lighting for Production in the Factory.* General Electric Company, Cleveland, 1939

[94] A. H. Taylor, *Illum. Eng.*, **37**, 19 (1942).

[95] S. E. Slocum, *Noise and Vibration Engineering.* Van Nostrand, New York, 1931.

[96] *Architectural Record*, **87**, 66 (Jan. 1940).

[97] J. S. Parkinson, *Trans. ASHVE*, **43**, 95 (1937).

[98] H. Kunen, *Acoustics in Air Conditioned Enclosures.* Anemostat Corporation of America, 1939.

[99] V. O. Knudsen, *Trans. ASHVE*, **38**, 211 (1932).

exhaustion, indigestion, and fatigue to temporary deafness and even permanent injury to the ears.[100-103a] A great deal has been learned about human hearing by laboratory experiments on small animals such as mice, rats, cats, and dogs, and this work became the basis for histological examination of human material after death to establish the fact that real and permanent damage occurs from exposure to excessive industrial noise. The predominant frequency range of the noise exposure of long duration, the frequency range of deafness or hearing impairment, and the position of tissue damage in the cochlea are all correlated, according to extensive hearing research by many persons.

High-frequency sounds are more annoying and damaging than sounds of low frequency, even though the ear is most sensitive to the frequency range of 800 to 1200 cycles per second. Therefore the permissible sound level should be based somewhat on the quality of the noise. Wartime experience gave ample evidence of the difficulty of establishing a simple standard of permissible noise, for workers were exposed to sound levels anywhere from 90 to 130 decibels for brief and extended periods, and some of the high-frequency, 90-decibel noises were the most unbearable of all. Furthermore, intermittent and sudden noises seem worse than steady loud noises, from the standpoint of the effect on the entire nervous system. Therefore, brevity of noise exposure is not necessarily preferable to prolonged noise, if it concentrates a tremendous noise shock into a fraction of a second.

Personal protection against noise and vibration assumes many forms. Protection against air-borne noise is obtained by pliable materials inserted into the outer ear, such as wax, cotton, plastic, or soft rubber. Protection against bone-conducted noise and vibration requires the use of soft-soled shoes, felt or rubber mats, and chairs or platforms mounted on springs or other shock absorbers. These methods, however, are to be recommended only when it has been found impossible or impracticable to prevent or reduce the noise and vibration at its source, or to reduce the intensity reaching the occupants, by suitable installation of sound barriers and absorbers in the physical environment.

B. PREVENTION OF NOISE AND VIBRATION

Preventable noise and vibration is a form of industrial waste, relating both to human efficiency and material resources. As in all fields of conservation, the best method of control is prevention of damage and destruction at the source; the alternative approach is to correct or cure the effects of noise and vibration after they have been produced.[104-108]

[100] C. P. McCord, E. E. Teal, and W. N. Witheridge, *J. Am. Med. Assoc.*, **110**, 1553 (1938).
[101] "Industrial Noise," *Occupation and Health*. International Labor Office, Geneva, 1938.
[102] E. D. D. Dickson, *Pharm. J.*, **156**, 9 (1946).
[103] D. A. McCoy, *Arch. Otolaryngol.*, **39**, 327 (1944).
[103a] F. K. Berrien, *Psychological Bull.*, **43**, 141 (1946).
[104] S. E. Slocum, *Noise and Vibration Engineering*. Van Nostrand, New York, 1931.
[104a] J. P. Den Hartog, *Mechanical Vibrations*. McGraw-Hill, New York, 1940.
[105] A. B. Eason, *The Prevention of Vibration and Noise*. Henry Frowde and Hodder and Stoughton, London, 1923.
[106] W. A. Keetch, *Product Eng.*, **16**, 183 (1945).

Manufacturers of office machinery capitalized on the desire for a quiet work environment by redesigning and offering their modern machines as "noiseless," a justifiable term in view of the tremendous clatter prevailing in the larger offices a few decades ago. The same trend has developed in the field of manufacturing and processing machinery, in some cases to the point that production methods are radically altered. Welding replaces riveting, hydraulic presses displace the old drop-hammer, V-belts replace whining gears, and advanced foundry practice reduces or eliminates casting chipping and grinding. All such efforts at mechanical improvement can be ultimately profitable because " a noisy machine is an inefficient machine."

Even the metallic impact so common wherever metal products are created can now be damped to reduce both the shock and noise at the source. Chamberlain of Michigan State College has developed a "hydropneumatic metal" that can be used as inserts in hammers, punches, and dies, and as durable shock-absorbing mounts for heavy presses and reciprocating machinery. It was used successfully during World War II to insulate delicate naval equipment from the shock of near-by super-bomb explosions under water, and to prevent the fracture of ankles and legs of naval personnel exposed to the same shock waves. It also replaced nonmetallic mounts for heavy aircraft engines, giving longer and more dependable vibration insulation.

Acoustical engineering has grown rapidly during the past decade as a result of the difficult demands of broadcasting studios. The results have spread to other construction projects where sound control is desired, and now we have a great variety of metallic and nonmetallic sound absorbers available for capturing the noise that cannot be readily prevented. An interesting application was the fabrication of ventilated snag grinding booths with sound-absorbing panels made of perforated metal and rock cork.[109] Industry has built special soundproof rooms for testing the sound characteristics of products and for insulating office and clerical personnel from noisy factory environments. In fact, it has been possible to construct rooms with sound levels low enough to be actually depressing to normal persons.

A recent dramatic use of sound-absorbing structural materials was the installation of open-front telephone booths in the newest New York subway. The three walls of acoustical material make it possible to carry on a telephone conversation in the presence of the clatter of passing trains.

C. MEASUREMENT AND ANALYSIS OF NOISE

The intensity of sound energy and the loudness sensation produced on the ear cannot be described on identical scales. Table 2 compares the scales of intensity and loudness, and indicates the tremendous range of audible energies between the threshold of hearing and the threshold of feeling at the eardrum.

[107] C. P. McCord and J. D. Goodell, *J. Am. Med. Assoc.*, **123**, 476 (1943).

[108] H. J. Sabine and A. Wilson, "Control of Industrial Noise," outline of discussion at the seminar conducted by the U.S. Pub. Health Service at St. Louis, May 6. 1944.

[109] A. H. Allen, *Foundry*, **69**, 60 (Sept., 1941).

TABLE 2

Comparison of Scales of Sound Intensity and Loudness

Identification	Decibel scale of intensity	Arithmetic scale of intensity	ASA proposed loudness scale[109a]
Threshold of feeling (varies with frequency)	120 110 100	1,000,000,000,000 100,000,000,000 10,000,000,000	560,000 220,000 88,000
Pneumatic drill at ten feet	90 80 70	1,000,000,000 100,000,000 10,000,000	38,000 17,000 8,000
Ordinary conversation at three feet	60 50 40	1,000,000 100,000 10,000	4,400 2,200 1,000
Tick of watch at three feet	30 20 10	1,000 100 10	360 100 14
Threshold of hearing at 1000 cycles/sec. (energy approx. 10^{-16} w./sq.cm.)	0	1	1

A logarithmic scale is much more convenient than an arithmetic scale for sound-level measurements or comparisons, and the *decibel* (or *phon* in some countries) has been generally adopted as the logarithmic unit for sound measurements. The bel is the base-10 logarithm of actual sound intensity, which is simply multiplied by 10 for the more convenient decibel scale.

Sound measurement may be either objective or subjective. In the objective method, physical instruments record electrically the quantity of energy or acoustical pressure, while in the subjective method, the human ear is used as a sound comparator. The tuning fork and the audiometer are subjective instruments. They are usually employed to determine the masking effect of a sound or noise. Objective instruments may either determine the sound levels in decibels without regard to frequency, or they may be equipped to analyze noise according to its component frequencies. The latter type of instrument requires considerably more skill in operation and interpretation than does a sound-level meter.

IV. Sanitary Conditioning

A well-lighted, heated, and sound-conditioned factory or office is certain to be also a sanitary workplace, because employers and employees both have realized the needs for industrial sanitation much longer than they have understood the requirements for light, sound, and air conditioning. In fact, the state laws and city ordinances throughout the country have for several decades been quite spe-

[109a] Proposed Standards for Noise Measurement, as adopted June 26, 1933 by the American Standards Association Committee on Acoustical Measurements and Terminology. *J. Acoust. Soc. of Amer.*, 5, 109 (Oct. 1933)

cific on sanitary requirements in public places, and the agreement on specifications has been strengthened by the appearance in 1935 of a code approved by the American Standards Association and sponsored by the United States Public Health Service.[110]

Many state departments of health and labor and other organizations have issued bulletins on such subjects as housekeeping,[111] industrial waste disposal, drinking facilities, toilet facilities, cross connections between industrial and potable water supplies,[112, 113] and the hazards of back siphonage due to improper plumbing, as well as the installation of tanks or vats of dangerous liquids in a manner that permits their contents to enter the drinking-water-supply system.

"The Installation and Maintenance of Toilet Facilities in Places of Employment" is the subject of a very thorough survey of the provisions of state laws throughout the country.[114] A similar survey has been made on "Sanitary Drinking Facilities, with special reference to drinking fountains."[115–117]

Figure 5 indicates the type of information required for the proper location of industrial sanitary facilities. Some codes and laws are definite concerning space requirements and clearances, and they should be consulted to avoid conflicts and oversights when remodeling or building.

Industrial eating facilities generally are required to comply with the ordinances or laws relating to public eating places in force in the vicinity, which are designed along the lines of well-developed communicable disease-preventive technics.[118] The necessity for rapid feeding of large groups of industrial workers has accentuated the requirement of strict control of sanitary conditions in factory cafeterias.[119]

The sanitary engineer is a specialist whose services are just beginning to enter large-scale industry as a professional entity. His employment in the past has generally been in the capacity of complete engineering control of environmental conditions following a period of specialized training in industrial hygiene technics. However, the problems of food, water, and milk control, and sewage and waste disposal in large industrial properties are becoming extensive enough to deserve

[110] (Industrial sanitation in manufacturing establishments), *ASA Code Z4.1-1935.* Sponsored by U.S. Pub. Health Service, New York.

[111] R. F. Vincent, *The Industrial Housekeeping Manual.* Natl. Foremen's Institute, New York, 1945.

[112] R. F. Goudey, *J. Am. Water Works Assoc.*, **33**, 39 (1941).

[113] F. M. Dawson and A. A. Kalinske, *Report on Plumbing Cross-Connections and Back-Siphonage Research.* Natl. Assoc. Master Plumbers, Washington, D.C., 1938.

[114] *Women's Bureau, U.S. Dept. Labor Bull.* No. **99** (1933).

[115] *Women's Bureau, U.S. Dept. Labor Bull.* No. **87** (1931).

[116] "Final Report of the Joint Committee on Plumbing of the Public Health Engineering Section of the American Public Health Association and the Conference of State Sanitary Engineers, October, 1930," *U.S. Pub. Health Repts.*, **46**, 170 (1931).

[117] "Final Report of the Committee on Sanitary Drinking Fountains," *J. Am. Water Works Assoc.*, **11**, 483 (1924).

[118] *U.S. Pub. Health Bull.* No. **280** (1943).

[119] J. M. Lents, *Factory Management and Maintenance*, **103**, 124 (Dec., 1945).

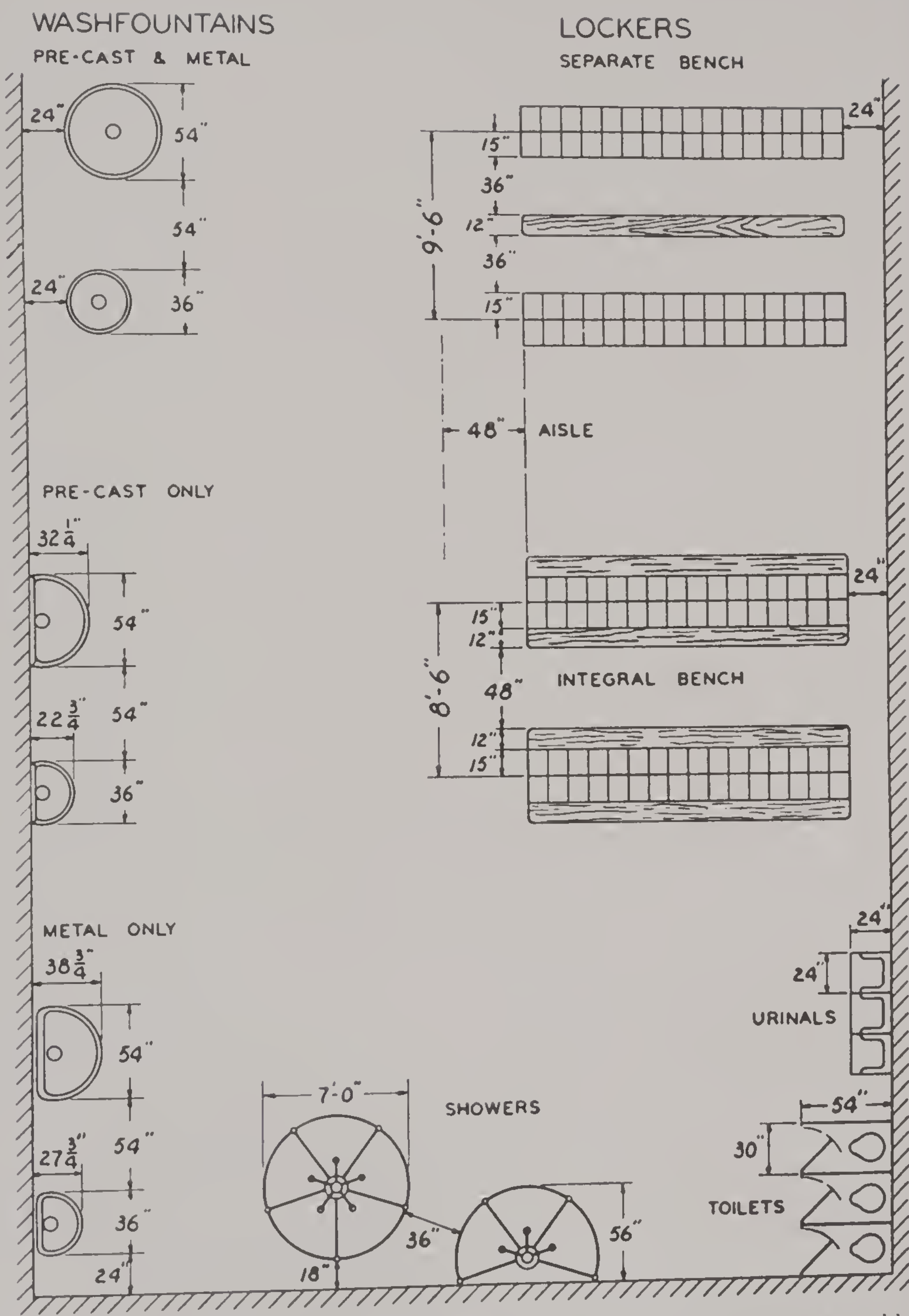


FIG. 5. Minimum practical clearances for washfountains, circular showers, toilets, and lockers (*courtesy Bradley Washfountain Company*).

the attention of a full-time sanitary engineer in addition to the industrial hygiene chemist, ventilating engineer, and safety engineer.

Such service might well be augmented by an illuminating engineer and a sound-control engineer to round out a more versatile organization of complete environmental engineering. Co-ordination of the work of such an organization is conceived as the responsible task of a widely experienced environmental engineer, whose job in industry may be closely parallel to and in some cases identical with that of some plant engineers of the present. The special distinction of the industrial environmental engineer is his knowledge of, and concern for, the integrated environmental requirements of human beings for efficient, safe, healthful, and comfortable employment. (See description of the industrial hygienist, Chapter Three.)

CHAPTER SIX

Physiological Effects of Abnormal Atmospheric Pressure*

HEINZ SPECHT

I. Introduction—Historical Background

The effects of the pressure exerted by the atmosphere upon the body, especially those that follow changes in this pressure, for convenience are considered in two classes, linked by the common physical attributes of gases. They comprise those found respectively: (*1*) in the range from normal barometric pressure to positive pressures met in diving and caisson work, and (*2*) in the range from normal to the reduced pressures incident to ascent into the atmosphere. As will be seen subsequently, certain details of the response to these two alterations in atmospheric pressure are different and necessitate separate discussion. In general, however, there is a continuity of response that has permitted a mutual acceleration of understanding of problems arising in these fields.

Historically, the elucidation of essential factors under both conditions rests on observation and practices of long standing, on the one hand in the diving industry, and on the other hand in agriculture and mining in mountainous areas, which have been implemented from ancient times by special knowledge, uncritical though it may seem in the light of more recent observation and experiment.

It is probable that pearl and sponge diving offered the earliest and most frequent industrial encountering of effects of compressed air. It seems likely that no realization of the physiological aspects existed until the time of Aristotle,[1] and then

* The author wishes to acknowledge the helpful criticism of the text by Dr. J. N. Stannard, Lt. U. S. N. R., Research Division, Bureau of Medicine and Surgery, Washington, D. C., Dr. W. J. Bowen and Dr. H. L. Andrews of the Industrial Hygiene Research Laboratory, National Institute of Health, Bethesda, Maryland. Much helpful discussion on controversial points was carried on with the staff of the Aviation Medicine Unit of the Industrial Hygiene Research Laboratory, National Institute of Health.

[1] R. Heller, W. Mager, and H. Schrötter, *Luftdruckerkrankungen mit besonderen Rücksichtigung der sogenannten Caissonkrankheit*. Vol. I, Hölder, Vienna, 1900.

only to the extent that he wrote of the practicality of inverting a kettle of air over the head as an aid in prolonging diving operations. Roger Bacon is reported to have invented a diving bell about 1250 A.D.[1,2] It was not until the seventeenth century that advances in diving technique were made rapidly. The advances made in that century served to recover the riches sunk with the Spanish Armada.[3] It was another century before pumps were used to supply air to divers, and it was with this means of prolonging diving time that intimations of physiological factors began to appear in the scientific writings. It was no longer a matter of "fresh air" but the realization that compression and more especially decompression were hazardous proceedings requiring deliberate and slow schedules for the attainment of gaseous equilibrium between the body and its environment. A logical basis for decompression was not discovered until Paul Bert[1,2,4] did his fundamental work on the effects of atmospheric pressure on the body.

The effects of rarified atmospheres were known in ancient times but the only significant deductions were concerned with their geographic distribution. Thus, the inhabitants of Alpine, Himalayan, and Andean regions were known to be industrious and healthy people casually undifferentiable from the lowlanders, yet the latter in travels through these regions collapsed or at least were ill and incapable of exertion. However Acosta, in 1590,[1,2] wrote that in trans-Andean trips even the natives were affected by extreme altitude and he rightly concluded that the "fine and thin air" was unsuited to the requirements of respiration.

It was not until abrupt ascent into the atmosphere became feasible that the pioneer balloonists found—by bitter experience—the necessity for detailed knowledge of the effects of lowered atmospheric pressure on the body. It was again the researches of Paul Bert[4] from 1871 to 1883, spurred on by the tragic outcome of ascents of Sivel, Croce-Spinelli, and Tissandier (1875), that started the analysis of these effects and laid a rational groundwork for the entire field.

In essence, the problems in physiology presented by abnormal atmospheric pressure deal with the vagaries of the physical solution of gases in the body fluids, the pressure-labile chemical changes of oxygen and carbon dioxide in the body, and the concomitant effects of these factors on the complex systems of adjustment that the mammalian organism, in particular, has evolved.

Because of certain differences, in various factors, that exist between the two types of abnormal pressure, increased and reduced pressure will each be considered separately and then followed by a discussion of the common properties. In order to understand the intimate difficulties encountered by the body in each of the two ranges of pressure it is necessary to recapitulate the properties of gases of the atmosphere; first, with respect to each other and their geographical distribution, and

[2] Heller *et al., op. cit.,* Vol. II.

[3] Meyer, *Conversations Lexicon.* 5th ed., Bibliographisches Institute, Leipzig and Vienna, 1893.

[4] P. Bert, *La pression barométrique.* Available in English as *Barometric Pressure,* M. A. and F. A. Hitchcock, trans., College Book Co., Columbus, Ohio, 1943.

second, with respect to their individual characters. (For a detailed treatment of the subject see the excellent work of Humphreys.[5])

II. Properties of the Atmosphere

A. COMPOSITION

The composition of the atmosphere near the earth's surface is discussed in Chapter Seven (which see), and therefore the components will not be tabulated here.

With the exception of carbon dioxide and ozone, the gases normally present in the air are distributed in relatively unvarying percentages from the level of depressions (−1292 ft. in the Dead Sea Basin) to an altitude of about 65,000 ft. Above this altitude there is no thermal mixing of the atmosphere and there is evidence that a progressive decrease in the concentration of the heavier gases occurs, as a result of gravitational separation. This level is above the altitude at which, on theoretical grounds, the boiling point of water in the body would be attained and far above the level at which pure oxygen will no longer suffice for supplying the metabolic needs. The composition of the atmosphere at these altitudes is mainly of engineering interest in the construction of stratosphere craft depending on ambient gases for pressurization of cabins.

The presence of such a variable constituent as ozone is accounted for by different theories. Besides local concentrations due to electrical discharges through the atmosphere there is a diffusion of ozone downward from extreme altitudes at which oxygen is thought to be converted to ozone by the absorption of energy from the sun.[6] Its instability prevents any accumulation to deleterious concentrations, as far as is known, in the vital altitude range given above.

Carbon dioxide is present in appreciable concentration only near the surface of the earth and may accumulate to a variable extent only in confined or circumscribed areas in which combustion of carbon or other release of carbon dioxide is taking place. In nature it may become a limiting factor for life, for example in certain grottoes where various processes free carbon dioxide from the rock to accumulate in the air in high concentration.[7] Carbon dioxide is also often encountered in dangerous concentration in caisson work, in mines, and in tunnels.[4]

In general, water vapor in the external air does not limit the use of the atmosphere for respiratory purposes but, as will be seen later, at high altitudes water vapor can physically displace other gases from the lungs. As far as can be ascertained, its concentration in air of caissons and tunnel heads produces no serious deleterious effects. In the external atmosphere it attains a very low value at the lower level of the isothermal layer[6] (stratosphere).

The only instances of significant concentrations of abnormal constituents and excessive concentrations of normal constituents are in situations similar to the above, that is, in confined or restricted areas. Conditions often are aggravated by

[5] W. J. Humphreys, *Physics of the Air*. 3rd ed., McGraw-Hill. New York. 1940.
[6] S. Ruff and H. Strughold, *Grundrisse der Flugfahrtmedizin*. Barth, Leipzig, 1939.
[7] E. L. Quinn and C. L. Jones, *Carbon Dioxide*. Reinhold, New York, 1936.

the fact that these abnormal constituents form layers whose concentrations are inimical to life. In any case, the factor of natural positive atmospheric pressure is of importance only because chemical reactions in metabolic systems depend in many cases on the partial pressure of the gaseous reactants, and thus identical concentration ratios may have widely different effects as the barometric pressure varies. The discussion of toxic effects of abnormal air constituents is not germane to this chapter.

B. PHYSICAL ATTRIBUTES OF ATMOSPHERIC GASES. FUNDAMENTAL PHYSIOLOGICAL ASPECTS

A visualization of the properties of gases is based on the kinetic theory of matter. Briefly stated, this assumes that gas molecules are in constant motion with an average velocity that is dependent on the temperature. They travel in straight lines until impact with another molecule of any kind changes their direction of motion and velocity. Pressure is exerted by a gas in the sense that force is applied by the impinging of its molecules upon all surfaces. This pressure is measured as force per unit area. The intermolecular distances in a gas are normally greater than those in a liquid or a solid, the latter differing mainly in the assumption that the molecules of a liquid slide over and about each other while those in a solid are fixed in relation to each other. More specifically, the following attributes of gases may be described here:

1. Mass and Weight

Mass may be defined as the amount of matter in a substance. It has the properties of inertia and of attraction for other masses. Mass is measured by the acceleration produced when a standard force acts on the inertia of the substance. It is specific for each kind of molecule. The mass of a substance multiplied by the acceleration due to the earth's attraction (gravity) is called its weight.

2. Density

This property of gases, common to all matter, is defined by the relation of mass or weight to unit volume. Thus at 1 atm. pressure and at 0° C.[5] 1.429 g. per liter is the density of oxygen; 1.251 of nitrogen; 1.9769 of carbon dioxide; 0.179 of helium; and 1.293 of air. The density of a gas is directly proportional to the pressure exerted by it (Boyle's law) and inversely proportional to its absolute temperature (Charles' law).

3. Compressibility

The property of compressibility is almost exclusively an attribute of gases. It describes the ready alteration of the average intermolecular distances in gases on the application of force and is an essential expression of the kinetic concept of the structure of matter. When a gas is compressed, if the temperature remains the same, the pressure rises in proportion to the increase in the number of molecules per unit volume. This change in pressure is identical with a change in density since the weight per unit volume has increased in the same proportion. The converse relation is true on rarefaction of a gas.

If now we compare a column of gas molecules to a column of bricks it is apparent that each unit will bear the weight of all above it in some manner. The downward force exerted on any brick can be described by its position below the top one, in terms of the unit weight of a brick, and the number of bricks above this one; the next below it bears this force plus one brick more, etc. The density of the brick clay is constant because it is a solid. In the gas there is a relatively large distance between molecules, which decreases as the force exerted on them increases. Even though there is probably no more than one contact per molecule on the average at any one instant, the structure is maintained by the molecules shuttling up and down until they strike the next adjacent one (disregarding for the moment all components to the sides). In such a column the number of molecules per unit height is greater at the bottom than at the top and it follows that the density is changed accordingly. This means that to ascertain the weight of the gas lying above, at any level, we must add the weights of a series of units of gas each a little lighter than the unit below it. The rate of decrease in weight of these units can be roughly described as logarithmic and this determines the shape of the curve drawn through the atmospheric pressure values at different altitudes. Figure 1 shows this relation when the proper corrections are included for the known average temperature of the air at the various altitudes and for other factors of real but minor importance.

From Figure 1 it can be seen that the atmospheric pressure is reduced to one half at about 17,500 ft., to one quarter at about 33,500 ft., etc. Actually some 99 per cent of the atmosphere is contained in the lower 18 to 19 miles of the gaseous envelope of the earth, and only about the lower two miles of it are habitable without marked restrictions to warm-blooded animals.[6]

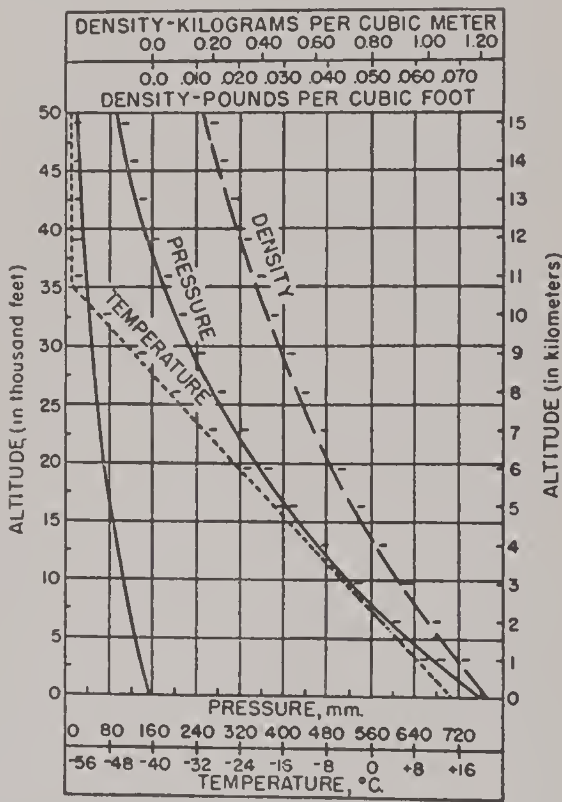


FIG. 1. Standard atmosphere chart officially adopted by all interested United States Government organizations for aeronautics and related purposes.[8] The values for the temperature, pressure, and density at all altitudes agree closely with the yearly average of United States meteorological data at 40° North latitude. See National Advisory Committee for Aeronautics, *Tech. Repts.* 147, 218, and 246 for formulas and complete tables.

[8] W. G. Brombacher, Standard Atmosphere Chart, *Bur. Standards Misc. Pub.* No. 82 (1927).

The pressure exerted by the weight of the atmosphere is exerted radially at any one point in proportion to the amount of overlying gas, as discussed above, and it is ordinarily measured by utilizing the fact that the atmosphere will support the weight of a column of fluid (oil, water, mercury, etc.) of a length inversely proportional to its specific gravity. Thus the standard atmosphere at sea level will support a column of mercury 760 mm. in length, and this is known to exert a pressure of 14.66 p.s.i. It is customary for the sake of convenience to use the height of such a barometer as a measure of atmospheric pressure.

It is apparent that increased pressures in the open atmosphere follow extensions of the relations discussed above for conditions at altitude, in fact, the altitudes shown

TABLE 1

Altitude–Pressure–Temperature Table for 500-Feet Intervals Ranging from −1000 to 80,000 Feet[9]

Altitude, ft.	Pressure		Temperature, °C.	Mean temperature, °C.	Altitude, ft.	Pressure		Temperature, °C.	Mean temperature, °C.
	in. Hg	mm. Hg				in. Hg	mm. Hg		
−1,000	31.02	787.9	17.0	16.0	15,500	16.54	420.2	−15.7	−0.6
−500	30.47	773.8	16.0	15.5	16,000	16.21	411.8	−16.7	−1.2
					16,500	15.89	403.5	−17.7	−1.7
0	29.921	760.0	15.0	15.0	17,000	15.56	395.3	−18.7	−2.2
500	29.38	746.4	14.0	14.5	17,500	15.25	387.3	−19.7	−2.7
1,000	28.86	732.9	13.0	14.0	18,000	14.94	379.4	−20.7	−3.2
1,500	28.33	719.7	12.0	13.5	18,500	14.63	371.7	−21.7	−3.7
2,000	27.82	706.6	11.0	13.0	19,000	14.33	364.0	−22.6	−4.3
2,500	27.31	693.8	10.0	12.5	19,500	14.04	356.5	−23.6	−4.8
3,000	26.81	681.1	9.1	12.0					
3,500	26.32	668.6	8.1	11.5	20,000	13.75	349.1	−24.6	−5.3
4,000	25.84	656.3	7.1	11.0	20,500	13.46	341.9	−25.6	−5.8
4,500	25.36	644.2	6.1	10.5	21,000	13.18	334.7	−26.6	−6.3
					21,500	12.90	327.7	−27.6	−6.9
5,000	24.89	632.3	5.1	10.0	22,000	12.63	320.8	−28.6	−7.4
5,500	24.43	620.6	4.1	9.5	22,500	12.36	314.1	−29.6	−7.9
6,000	23.98	609.0	3.1	9.0	23,000	12.10	307.4	−30.6	−8.4
6,500	23.53	597.6	2.1	8.5	23,500	11.84	300.9	−31.6	−9.0
7,000	23.09	586.4	1.1	8.0	24,000	11.59	294.4	−32.5	−9.5
7,500	22.65	575.3	0.1	7.5	24,500	11.34	288.1	−33.5	−10.0
8,000	22.22	564.4	−0.8	7.0					
8,500	21.80	553.7	−1.8	6.5	25,000	11.10	281.9	−34.5	−10.5
9,000	21.38	543.2	−2.8	6.0	25,500	10.86	275.8	−35.5	−11.1
9,500	20.98	532.8	−3.8	5.5	26,000	10.62	269.8	−36.5	−11.6
					26,500	10.39	263.9	−37.5	−12.1
10,000	20.58	522.6	−4.8	5.0	27,000	10.16	258.1	−38.5	−12.7
10,500	20.18	512.5	−5.8	4.5	27,500	9.94	252.5	−39.5	−13.2
11,000	19.79	502.6	−6.8	4.0	28,000	9.72	246.9	−40.5	−13.7
11,500	19.40	492.8	−7.8	3.5	28,500	9.50	241.4	−41.5	−14.3
12,000	19.03	483.3	−8.8	2.9	29,000	9.29	236.0	−42.5	−14.8
12,500	18.65	473.8	−9.8	2.4	29,500	9.08	230.7	−43.4	−15.3
13,000	18.29	464.5	−10.8	1.9					
13,500	17.93	455.4	−11.7	1.4	30,000	8.88	225.6	−44.4	−15.9
14,000	17.57	446.4	−12.7	0.9	30,500	8.68	220.5	−45.4	−16.4
14,500	17.22	437.5	−13.7	0.4	31,000	8.48	215.5	−46.4	−16.9
					31,500	8.29	210.6	−47.4	−17.5
15,000	16.88	428.8	−14.7	−0.1					

[9] W. G. Brombacher, Altitude-Pressure Tables Based on the United States Standard Atmosphere, *Natl. Advisory Comm. for Aeronaut. Rept.* No. 538 (republished 1942).

in Table 1 are extended to −1000 ft. to facilitate calculations for depressions. On the other hand, the more generally practical use of increased pressures is in connection with the displacement of water while diving and of water and solids (such as sand and mud) in caisson work. In these cases the weight of the air becomes a constant and usually negligible factor upon which is superimposed the pressure exerted by the column of fluid above the free surface in such an enclosed system. In diving a uniform, or arithmetic, increment in pressure per unit depth is added on descent. Due to the relatively moderate depths that can be withstood in diving, and the nearly incompressible nature of fluids, this increment is practically constant. In seawater it is about 1 atm. for every 33 ft., or roughly ½ p.s.i. per foot.

TABLE 1 (*continued*)

Altitude–Pressure–Temperature Table for 500-Feet Intervals Ranging from −1000 to 80,000 Feet[9]

Altitude, ft.	Pressure		Temperature, °C.	Mean temperature, °C.
	in. Hg	mm. Hg		
32,000	8.10	205.8	−48.4	−18.0
32,500	7.91	201.0	−49.4	−18.6
33,000	7.73	196.4	−50.4	−19.1
33,500	7.55	191.8	−51.4	−19.6
34,000	7.38	187.4	−52.4	−20.2
34,500	7.20	183.0	−53.4	−20.7
35,000	7.04	178.7	−54.3	−21.3
35,332	6.93	175.9	−55.0	−21.6
35,500	6.87	174.5	−55.0	−21.8
36,000	6.71	170.4	−55.0	−22.3
36,500	6.55	166.4	−55.0	−22.8
37,000	6.39	162.4	−55.0	−23.3
37,500	6.24	158.6	−55.0	−23.8
38,000	6.10	154.9	−55.0	−24.3
38,500	5.95	151.2	−55.0	−24.8
39,000	5.81	147.6	−55.0	−25.2
39,500	5.68	144.1	−55.0	−25.6
40,000	5.54	140.7	−55.0	−26.0
40,500	5.41	137.4	−55.0	−26.4
41,000	5.28	134.2	−55.0	−26.8
41,500	5.16	131.0	−55.0	−27.2
42,000	5.04	127.9	−55.0	−27.6
42,500	4.92	124.9	−55.0	−28.0
43,000	4.80	122,0	−55.0	−28.3
43,500	4.69	119.1	−55.0	−28.6
44,000	4.58	116.3	−55.0	−29.0
44,500	4.47	113.5	−55.0	−29.3
45,000	4.36	110.8	−55.0	−29.6
45,500	4.26	108.2	−55.0	−29.9
46,000	4.16	105.7	−55.0	−30.2
46,500	4.06	103.2	−55.0	−30.5
47,000	3.97	100.7	−55.0	−30.8
47,500	3.873	98.38	−55.0	−31.1
48,000	3.781	96.05	−55.0	−31.4
48,500	3.693	93.79	−55.0	−31.7

Altitude, ft.	Pressure		Temperature, °C.	Mean temperature, °C.
	in. Hg	mm. Hg		
49,000	3.605	91.57	−55.0	−31.9
49,500	3.520	89.41	−55.0	−32.2
50,000	3.436	87.30	−55.0	−32.4
51,000	3.276	83.22	−55	—
52,000	3.124	79.34	−55	—
53,000	2.978	75.64	−55	—
54,000	2.839	72.12	−55	—
55,000	2.707	68.76	−55	—
56,000	2.581	65.55	−55	—
57,000	2.460	62.49	−55	—
58,000	2.346	59.58	−55	—
59,000	2.236	56.80	−55	—
60,000	2.132	54.15	−55	—
61,000	2.033	51.63	−55	—
62,000	1.938	49.22	−55	—
63,000	1.847	46.92	−55	—
64,000	1.761	44.73	−55	—
65,000	1.679	42.65	−55	—
66,000	1.601	40.66	−55	—
67,000	1.526	38.76	−55	—
68,000	1.455	36.95	−55	—
69,000	1.387	35.23	−55	—
70,000	1.322	33.59	−55	—
71,000	1.261	32.02	−55	—
72,000	1.202	30.53	−55	—
73,000	1.146	29.10	−55	—
74,000	1.093	27.75	−55	—
75,000	1.041	26.45	−55	—
76,000	0.993	25.22	−55	—
77,000	0.946	24.04	−55	—
78,000	0.902	22.92	−55	—
79,000	0.860	21.85	−55	—
80,000	0.820	20.83	−55	—

4. Partial Pressures

The pressure changes described above are shared by the constituent gases of the atmosphere in the ratio of their occurrence (Dalton's law) in air, or as modified in any gas space such as the alveoli of the lungs, etc. This situation follows from the kinetic concept of gases, since each species of molecule exerts its pressure throughout any definable space as if it were there alone. Thus, $P(\text{air}) = p'N_2 + p''O_2 + p'''H_2O + p''''$ inert gas, etc., where P(air) is the barometric pressure and p', p'', and so forth are the partial pressures of the several gases of the air. (Certain deviations from this simple relation may be expected under high positive pressures due to interference of different molecular species with each other.) Any change in the sum of these component pressures must be shared proportionately by the constituents. Thus, a curve describing the partial pressure of oxygen in air at different altitudes would be the line drawn about one fifth the distance from the ordinate axis for air pressure at any altitude in Figure 1. It will be seen later that the partial pressure of gases is most important in the physiology of gaseous exchange and actually forms the nucleus of all rational approach to the problems of the effects of abnormal atmospheric pressures upon living organisms.

The pressure–volume relationship of gases at constant temperature at any altitude is determined from Boyle's law (PV = constant) by the relation $P_1V_1 = P_2V_2$. By suitable arrangement the volume assumed by wet air at constant temperature at any altitude is calculable from the formula[10, 11]

$$V_2(\text{wet}) = V_1(\text{wet})\frac{P_1 - p\text{H}_2\text{O}}{P_2 - p\text{H}_2\text{O}}$$

where the symbols have the following significance: V_1 = the initial volume at ground level, V_2 = the resulting volume at altitude of the same weight of gas as contained in V_1, P_1 = the initial pressure at ground level, P_2 = the resulting pressure at altitude, and $p\text{H}_2\text{O}$ = the vapor pressure of water at the specified temperature.

5. Solubility or Absorption

To a greater or lesser extent all gases are soluble in other substances and, barring for the moment chemical reaction with the solvent, the concentration of gas dissolved is proportional to its pressure (partial pressure) above the interface of gas and solvent (Henry's law). The rate of solution depends on the difference between the frequency at which the gas molecules impinge on the surface and that at which the gas in solution tends to escape from solution, and on the nature of the solvent.

These facts are equally true of gases dissolved in body substances. The living organism exists in a state of dynamic equilibrium with the gases that impinge upon it.[12] The diffusion of gases through the outer skin of the body is of a low order as

[10] C. H. Fugitt, *U. S. Naval Air Training Bases, Pensacola, Fla., Project X-579, Rept. No. 1* (1945).
[11] Aero Medical Laboratory Staff, *AAF Manual* No. **25-2** (March, 1945).
[12] J. Sendroy, Jr., R. T. Dillon, and D. D. Van Slyke, *J. Biol. Chem.*, **105**, 597 (1934)

shown by Behnke and Willmon.[13] As far as practical considerations require, the gaseous exchange of the body is through the lung surface, where solution is effected readily.

It has been shown by Haldane[14] and others that the volume of oxygen passed by a human lung–blood interface per mm. Hg differential pressure (across the interface) varies from 25 to 56 ml. per minute, depending on the state of exercise. For carbon dioxide the value is at least 20 to 30 times as great. This ratio is remarkably similar to that of their solubilities in water in milliliters per milliliter of water at body temperature: $0.555/0.023 = 24/1$, although this correspondence may be fortuitous.

The greater solubility of carbon dioxide in water, as compared with oxygen, is due mainly to its tendency to form a hydrate with water and to ionize in solution. This tendency acts to decrease the partial pressure of carbon dioxide in the water and thus to maintain a greater difference in concentration across the interface than can be effected with inert gases.

As implied above, the solution of gases in the body is primarily a solution in water, and after this initial action further distribution depends on the diffusion, circulation, partition, and chemical combination, if any, in other body substances. The most important gas reservoir other than the blood and watery fluids of the body is its fat, since fat occurs in a relatively large quantity. Gas dissolved in fat has been shown by Behnke,[15] Gersh,[16] and others to be a major source of difficulty in caisson disease. Table 2 shows the solubilities of several atmospheric gases in water and

TABLE 2

Solubility of Atmospheric Gases in Water and Olive Oil at 38° C.[15]

Gas	Solubility, ml./ml.		Oil/water ratio
	Water	Olive oil	
Oxygen	0.023	0.112	4.9 :1
Nitrogen	0.0127	0.0667	5.24:1
Helium	0.0087	0.0148	1.7 :1
Argon	0.026	0.1395	5.32:1

olive oil and the ratio of these solubilities, indicating that at equilibrium a large amount of gas may be stored in the fatty tissues. The role of fat in aeroembolism is similar to that in decompression sickness. More will be said of it in the following sections. As far as other substances in the body are concerned, the capacity of the body for simple solution of gases is almost wholly due to the water or fat content, and no further distinction need be made here for this property.

The solution of gases in the body, including oxygen and carbon dioxide, was not readily analyzed by experiment until recently, although much work on the use of

[13] A. R. Behnke and T. L. Willmon, *Am. J. Physiol.*, *131*, 627 (1940–41).
[14] J. S. Haldane and J. G. Priestley, *Respiration.* Yale Univ. Press, New Haven, 1935.
[15] A. R. Behnke, *Bull. New York Acad. Med.*, *18*, 561 (1942).

gases for estimating cardiac output and lung function is in the literature. The converse, or desaturation, has been studied intensively in developing a means of obviating caisson disease and aeroembolism. Data on nitrogen elimination[15, 17] are shown graphically in Figure 2 and indicate the involvement of a system of at least two components; fat and water, for which an empirical approximation was developed. It has been shown further by Smith and Morales[18] that certain refinements in the consideration of physical constants of the various media for the accumulation of gases, the avenues of saturation and desaturation, and so forth, enable them to set up a general theoretical expression for the gain or loss of gases from the whole or any portion of the body. They consider the effects of blood volume, blood flow, tissue volume, surface presented, permeability, solubility, and gas concentration. This analysis is shown in Figure 3 to fit well with experimental data, and it is apparent that a rational and basically sound relation has been developed.

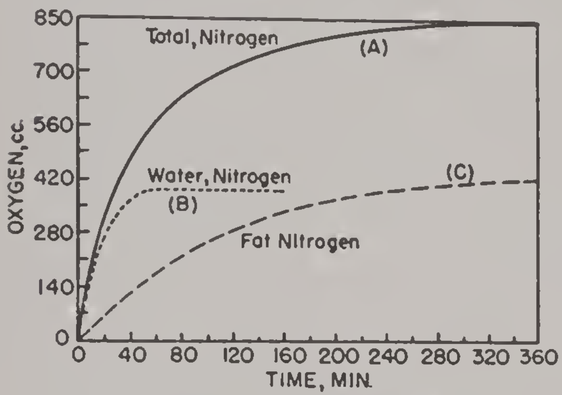


FIG. 2. Elimination curve for nitrogen.[15] Total nitrogen (A) represents the average of the values for nitrogen elimination from three men (average weight 64 kg.) who breathed pure oxygen at atmospheric pressure. Water nitrogen (B) and fat nitrogen (C) are hypothetical curves showing the absorption or elimination of nitrogen by the body solvents. The values for nitrogen on (A) are approximately the sum of corresponding values on (B) and (C).

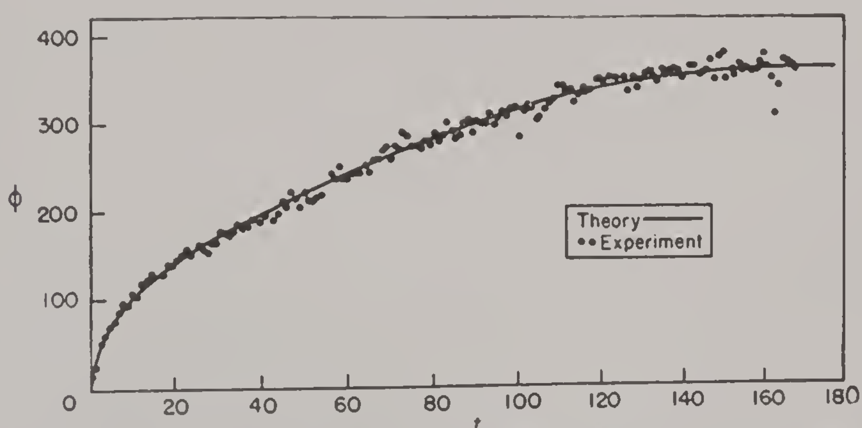


FIG. 3. Total nitrogen gas uptake by limb tissues.[19] ϕ, a function of tota nitrogen absorbed at any time t, is the counts of radioactive krypton at one minute intervals.

[16] I. Gersh and G. E. Hawkinson, *Naval Med. Research Inst., Research Project X-284, Rept.* No. *1* (1944).

[17] L. A. Shaw, A. R. Behnke, A. C. Messer, R. M. Thomson, and E. P. Motley, *Am. J. Physiol.*, **112**, 545 (1935).

[18] R. E. Smith and M. F. Morales, *Bull. Math. Biophysics* No. **6**, 125 (1944).

[19] R. E. Smith and M. F. Morales, *Bull. Math. Biophysics* No. **6**, 133 (1944)

6. *Temperature of the Atmosphere, Its Origin and Variation*

Since we are dealing generally with body temperature under conditions of reasonable functional integrity it would not seem that the environmental temperature plays any major role in the response to atmospheric pressure change. The greatest variation in body temperature lies probably between 28 and 40° C. In this range the solubility of gases generally falls with increased temperature, though the magnitude of the change is relatively small. The temperature coefficient of simple chemical reactions *in vivo* is found to be of a moderate order and is given by the Arrhenius relation which states that the rate of reaction is doubled or trebled for every 10° C. rise.[20]

On the other hand, certain physiological responses to temperature changes of very minor extent are exceedingly marked and important to the economy of gases in the body, though by indirection. A consideration of atmospheric temperature variation must be included here to be drawn upon later in explanation of certain responses to alterations in pressure at altitude.[20a]

The temperature of the atmosphere is due mainly to the energy absorbed from solar radiation, secondarily to that added by conduction or convection. For our consideration, the distribution of temperature in the two zones of the atmosphere nearest the earth is of interest. From the ground up to about 36,000 ft. there is found a variable temperature, the average value falling off with increase in altitude, and above this level there is a region of uniform temperature known as the isothermal layer. This uniform temperature, which extends to excessively high altitudes, is reported to be relatively constant at −55° C. (−67° F).[21] It is in this upper region that the ozone produced by absorption of ultraviolet radiation by oxygen in the outer layers is observed to gravitate in appreciable concentration. Because of the filtering action of these superior strata there is relatively little absorption of energy by the gases in the isothermal layer. Below the lower boundary of this layer, at about 36,000 feet, water vapor and solids in the atmosphere absorb energy in an appreciable amount, and the temperature rises gradually as the earth is approached until the characteristic temperature of the latitude is attained. On the other hand, owing to thermal displacement of air masses by convection and conduction of heat and by the absorption of reradiated energy from the earth's surface, there is often a great deal of random distribution of temperature. Thus, surface temperature may be colder than at several thousand feet directly above the ground, and several such inversions may be found above each other. These are found mainly over land masses and are part and parcel of the "weather." The mechanism is not important to this discussion. Further details may be found in Humphreys.[21] Local temperatures below the tropopause, or lower stratosphere level, as low as −120° F. have been recorded. It is important to point out that in contradistinction to the previous fact, aeronautical tables are calculated on the assumption that there is a constant temperature in the

[20] H. L. Blum, *Photodynamic Action and Diseases Caused by Light*. Reinhold, New York, 1941.

[20a] H. G. Armstrong, *Military Surgeon*, **79**, 133 (1936). H. G. Armstrong, *Principles and Practice of Aviation Medicine*, Williams & Wilkins, Baltimore, 1938.

[21] W. J. Humphreys, *Physics of the Air*, 3rd ed., McGraw-Hill, New York, 1940.

so-called isothermal region and that a regular increase in temperature on descent from this level to the ground is found. Thus the effect of the temperature variations on "pressure altitudes" in the atmosphere is of interest to the physiologist, who is concerned with the barometric value of any linear altitude and not with the actual height above sea level.

As far as increased pressures are concerned, it is evident that, except for heat added by compressing equipment, the temperature of the air or other gases will tend to equal that of the environment, for example in sea water it will range upward from 28.6° F., which is the freezing point of sea water of average salinity.

While the heat conductivity of gases is not affected by pressure, certain changes in heat loss from the body are to be expected from changes in pressure of the atmosphere, since the heat capacity of the air is changed and tends to alter the temperature differential necessary to maintain constant heat transfer from the body to the environmental gases. This effect is very marked for subjects in low pressure chambers at "altitude," and may cause wrong interpretation of the temperature sensations.

C. CHEMICAL ACTIVITY

The chemical activity of the gases of the atmosphere relevant to the physiology of atmospheric pressure in mammals is limited to that of oxygen and carbon dioxide. This limitation is mainly due to the fact that the energy levels needed for direct chemical reaction are not feasible in living systems. All reactions of gases depend, under these circumstances, either primarily or secondarily on catalysis of some type. The metabolic involvement of hydrogen and nitrogen has been substantiated for living forms as high as bacteria[22, 23] but mammals have not been found to possess the systems necessary for either hydrogen or nitrogen activation in the gaseous state. Enzymes for the activation of gaseous oxygen and carbon dioxide are integral to the metabolic processes of all mammals.[24] In common with reactions of other substances, the rate and equilibrium of the reaction of gases depend among other factors on the concentration of the gas, both relatively and absolutely; that is, the systems are pressure-labile within limits. This property is of utmost importance in the physiological analysis of the effects of atmospheric pressure.

In setting aside, at the beginning of the previous section (see B5), the fact that chemical reaction affects the solution of gases, it was intended only to reserve this complication for further discussion because, as will be seen in subsequent sections, it is of great importance in the exchange of gases between the atmosphere and the body fluids.

It may be fitting to point out at this time that the widely publicized[25] similarity between the status of flames and metabolic oxidations at altitude is a fallacious one, flames having actually only minor response to even extensive pressure changes but being markedly sensitive to relative concentration, while metabolic oxidations be-

[22] Alec H. Laurie, *Discovery Repts.*, **7**, 365 (1933).

[23] A. Krogh, *Nature*, **133**, 635 (1934).

[24] C. L. Evans, *Starling's Principles of Human Physiology*. 8th ed., Lea and Febiger, Philadelphia, 1941.

[25] *Life*, **12**, No. 8, 66 (1942).

have quite the opposite. The difference is in part due to the fact that in metabolic activities there exists always a solution phase between the free gas and the substance oxidized. Contrary to popular accounts[25, 26] a candle flame will continue to burn in air up to a simulated altitude of 57,000 ft., provided a large enough volume of air is used for the environment of the flame. A change in the character of flames at altitude[27] led to erroneous conclusions from experimental engineering data cited above.[28] The ultimate limitation on flame stability in the case of the candle results from the flame's being forced to recede from the wick in order to carry a sufficient quantity of oxygen to the flame front. Not only is vaporization of the fuel of the candle flame progressively inhibited, but also the flame literally blows itself out. It has, however, been possible to maintain hydrogen flames in air at altitudes somewhat in excess of that for the candle flame since combustion of hydrogen is not dependent on the melting and vaporization of the fuel by the heat of the flame.[29]

While relatively few data are at hand to indicate the quantitative effect of increasing atmospheric pressure on the metabolism of living systems, effects of oxygen and carbon dioxide at high pressure[30] indicate that marked influences on metabolism do occur.

1. Oxygen and Carbon Dioxide

The pressure-labile chemical combination of oxygen and carbon dioxide with the blood is a reciprocal relation involving the binding power of hemoglobin and bases in the blood complex for these two gases of the atmosphere. Essentially there is an involved chemical redistribution of ions between blood plasma and tissue solutes[31] for every change in partial pressure of the constituent gases. Under conditions of normal atmospheric pressure these relations are given by curves shown in Figures 4 and 5. Further codification of these relationships between the multiple factors known to affect this system has been developed by Henderson and his associates,[33, 34] but for the present

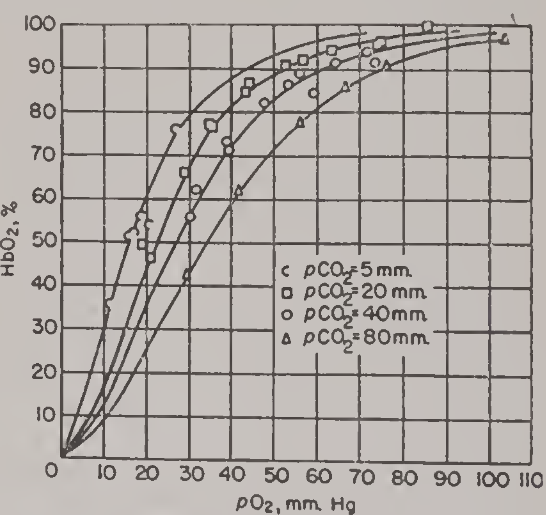


FIG. 4. Oxygen dissociation curves of blood of a man at work.[32]

[26] H. G. Armstrong and M. C. Grow, *Fit to Fly, a Medical Handbook for Fliers.* Appleton-Century, New York, 1941.

[27] S. Ruff and H. Strughold, *Grundrisse der Flugfahrtmedizin.* Barth, Leipzig, 1939.

[28] W. S. Weeks and R. K. Byerts, *Eng. Min. Jour.*, **141**, No. 10, 44 (1940).

[29] From unpublished data of the author.

[30] J. W. Bean, *Physiol. Revs.*, **25**, 1 (1945).

[31] A. V. Bock, H. Field, Jr., and G. S. Adair, *J. Biol. Chem.* **59**, 353 (1924).

[32] A. V. Bock, D. B. Dill, L. M. Hurxthal, J. S. Lawrence, T. C. Coolidge, M. E. Dailey, and L. J. Henderson, *J. Biol. Chem.* **73**, 749 (1927).

purpose these need not be discussed here in detail. It is sufficient to point out that, since dependence on partial pressure of the gases has been established, the relationship holds regardless of the external cause of the change in partial pressure.

Therefore, in the case of oxygen it is possible to interpret the partial pressure axis of the dissociation curve for hemoglobin in terms of altitude. In this case a correction for converting the atmospheric partial pressure to that actually found at the alveolar surface must be made. Figure 6 shows theoretical and equilibrium values for both carbon dioxide and oxygen pressures at the lung–blood interface at different altitudes. The deviations of the experimental data are due mainly to compensations of the body and not to the simple chemical relationships of the gases and their absorbent substrates.[35]

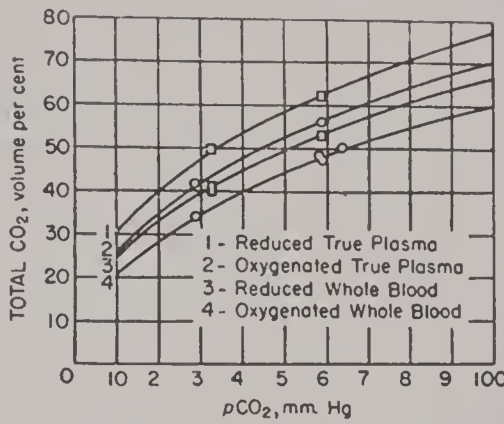


FIG. 5. Carbon dioxide dissociation curves of blood of a man at work.[32]

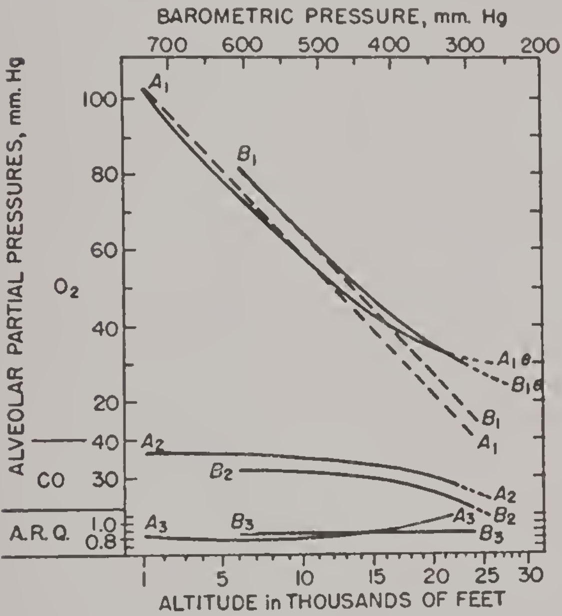


FIG. 6. Effect of decreasing pressure on alveolar oxygen and carbon dioxide partial pressures.[35] Curves A_1e, A_2, and A_3: average of experimental data, subjects acclimatized to 1,000 ft. (300 meters). Curves B_1e, B_2, and B_3: average of experimental data, subjects acclimatized to 6,200 ft. (1,900 meters). Curves A_1 and B_1: theoretical fall in oxygen partial pressure with no increased ventilation. A.R.Q. = alveolar respiratory quotient.

2. "Inert" Gases

In contrast to the properties of chemically active gases as discussed above, the behavior of the so-called inert gases of the atmosphere, such as nitrogen, argon, krypton, etc., is usually thought to be purely physical. Certainly under vital conditions in mammals there is no corroborated evidence that nitrogen gas can enter into chemical reactions.[36] On the other hand, observations at high positive pressures, by Behnke and Yarbrough[37] and others, have led to the postula-

[33] L. J. Henderson, A. V. Bock, H. Field, Jr., and J. L. Stoddard, *J. Biol. Chem.*, **59**, 379 (1924).

[34] L. J. Henderson, *Blood*. Yale Univ. Press, New Haven, 1928.

[35] W. R. Boothby, *Proc. Staff Meetings Mayo Clinic*, **20**, 209 (1945).

[36] A. Krogh, *Nature*, **133**, 635 (1934).

[37] A. R. Behnke and O. D. Yarbrough, *U. S. Naval Med. Bull.*, **36**, 549 (1938).

tion of a quasi-physical or chemical action that may be involved in the production of a "narcosis" under these conditions by nitrogen and argon and not by the lighter gases such as helium and hydrogen.[38] There does not seem to be at present any known cause for these effects except that the behavior of gases does not follow the usual relations when high pressures exist.

III. Effects of Increased Atmospheric Pressure on the Body

A. CHARGING OF THE BODY WITH GASES

1. Mechanical Effects

Mechanical effects of compression of the environmental gases on the fluid and solid constituents of the living system are negligible, due to the incompressibility of these constituents. On the other hand, since pressure is transmitted undiminished throughout these substances of the body, displacement of fluid or tissue into any gas space not continuous with the atmosphere is unavoidable. Such gas spaces are, unfortunately for those concerned, present in the body, particularly in the middle ear and various sinuses in the head; of lesser importance are the included abdominal and other gases.

In general the mechanical effects in natural diving are only quantitatively different from those in caisson diving, while suit diving adds a mechanical hazard called "the squeeze," which is really a macroscopic extension of the above principle, in that here the body is forced into the helmet if air pressure fails to balance water pressure. It is of considerable practical importance because collapse of the lungs with massive congestive hemorrhage results quite early in such cases.

The middle ear, including the mastoid sinus, has only intermittent connection with the external atmosphere through the soft-walled eustachian tube. On compression the eardrum and this pharyngeal structure, which is normally collapsed up to the point where it is enclosed in the bony structure of the head and thus forms a stopper, are pushed progressively inward. If voluntary opening of this tube is not effected by movement of the adjacent muscles during swallowing, then continued increase in pressure causes a displacement of the eardrum into the lumen of the middle ear with varying degrees of trauma, and, more importantly, the displacement of blood into the capillary lining of this cavity, resulting in transient reddening, petechial and massive hemorrhage, and occasionally rupture of the tympanum.[39] In addition, there is an early dulling of the hearing, which is due to the marked displacement of the incus, malleus, and stapes, preventing them from transmitting sound vibrations to the middle ear properly. According to the experience of the Royal Navy[40] it is found that some degree of acute drum trauma is produced in all but the most experienced pressure workers.

The action of increased atmospheric pressure on the various sinuses is only

[38] E. M. Case and J. B. S. Haldane, *J. Hyg.*, **41**, 225 (1941).

[39] E. D. D. Dickson, J. E. G. McGibbon, and A. C. P. Campbell, *J. Laryng. Otol.*, **58**, 465 (1943).

[40] *Roy. Naval Med. Bull.* No. **5**, 13 (1943). Abst. in *Bull. War Med.*, **4**, 305 (1944).

deleterious and painful when, as in the ear, the openings are not patent. In normal individuals this is rare, but it is a chronic condition with some individuals, generally associated with infection or malformations. Obviously, acute infection of the upper respiratory tract tends to produce this condition. When the openings of the sinuses are thus occluded an increase in atmospheric pressure will result in severe pain and varying degrees of trauma even with moderate pressure differences. This seeming disproportionality between cause and effect is due possibly to the rather large surface-to-volume ratio of most sinuses, allowing ready distension of large areas of capillaries. This distension leads to marked stimulation of deep pain receptors, with the observed sequelae of nausea, etc., due to autonomic discharge from this stimulation. As far as can be determined, reports from the older literature of mechanical trauma to the vascular system are to be attributed more to the various conditions enumerated above than to other gross hydraulic effects, as was formerly held.[41] It is true, however, that the blood is forced into the capillaries lining any such rigid-walled, isolated gas space and, depending on the tonic state, may result in hemorrhage. If we assume a normal capillary pressure of 40 mm. Hg, it takes only 1/19 atm. of positive pressure to double this value in the capillary bed of the ear or sinus. Clinical tests of capillary fragility are based on petechial hemorrhages in normal tissue with 50 mm. Hg pressure above normal![21]

Gases in the alimentary tract are, wherever located, subject to compression by the body tissues and for the most part do not cause any inconvenience beyond the displacement of the viscera, which in most cases can be of only a benign nature. As will be shown subsequently this does not absolve these gas entities from consideration since, unless passed as flatus, they expand on decompression.

There remains one more mechanical effect of compression which, while rare, is real and may produce drastic sequelae: this concerns the compression of the gases in the lungs. Offhand, no effect would be expected since almost continuous patency of the breathing passages is assumed. There must be recognized, however, the fact that, during rapid compression, closure of the glottis in swallowing or breath holding may result in compression of the lungs to such an extent that only with considerable difficulty can sufficient positive pressure be created by the thoracic musculature to release the glottal closure. Such cases have been observed on recompression from negative pressure, as will be discussed later. It is important, especially in experimental work, that warning against breath holding be promulgated during indoctrination and in the course of work while rapid compression is being effected.

Other effects of compression that are partly of a mechanical nature, such as the transient accumulation of carbon dioxide in the lungs and blood during inflow of gas on rapid compression of the atmosphere, as described by Bean,[30] are discussed under subsequent headings.

The extension of mechanical effects to conditions of pathology is not possible in this presentation, but reports of injury to pathological areas in the lungs on com-

[41] E. C. Hoff, *A Bibliographical Source-Book of Submarine and Compressed Air Medicine*. U. S. Government Printing Office, Washington, D. C., 1947.

pression are found in the literature[30] and argue strongly for thorough pre-employment medical examinations in occupations involving atmospheric pressure changes.

2. Solution of Gases in the Body

As indicated in the section on the solubility of atmospheric gases, the capacity of the blood and tissues for taking up gases is determined by two general characteristics that respond to partial pressure. That is, both the simple physical solution of gases in fluids and the pressure-labile chemical association of certain of them with solutes in the fluids and their cells are concomitantly affected by changes in pressure. Relatively small quantities of gas are taken up by the watery portion of the blood as is seen from Table 2, but it must be kept in mind that all gases passing to and from the tissues pass through the solution phase in the course of their transfer between tissue and atmosphere. In addition, at every stage of the transfer of gases there is, inescapably, a series of mediums through which gas exchange takes place, each of which has its own coefficient of diffusion, permeability, partition, and the like, which set up the parameters of the tissue–gas relationship with external pressure.

Smith and Morales[42] describe at least four phases in the attainment of saturation of tissues with inert gases by way of the lungs. Their analysis gives a curve of uptake with respect to time that, instead of having a uniformly changing slope, is characterized by an inflection or flattening in what they call the second stage of gas transfer. At this time the blood is taking in gas at a uniform rate, since it is presented at the lung surface at a limited rate, in conformity with the speed of circulation. These transient phenomena are of interest here mainly in that they show the system to be first serially, then concomitantly, affected by gas pressure changes during an increase in pressure. It is evident, further, that by virtue of these limiting phases the degree of saturation or concentration of gases in the tissues is limited with respect to time.

Although the general nature of the uptake of gases in the different tissues of the body is similar, the effectiveness of the distributing system varies and this further affects the time required for saturation. The partition of gases between fatty, glandular, neural, and muscular tissues is obviously dependent at equilibrium on the solubility of the gases in the various materials comprising the cell structures, the protoplasm, and the inclusions, but at any time short of equilibrium the major factors may be considered to be the transport and access of the gases to the cells. These factors are usually spoken of as the vascularization of the tissue. Gersh[43] has shown that the ratio of capillary surface to the total cell volume of fatty tissues is 51.9 and of tissues poor in fat is 222.2. He indicates further that this disparity is due to the included fat alone, since the same ratio on the basis of volume of active protoplasm exceeds that found for muscle.

Essentially it is seen that the fat depots are large nitrogen reservoirs with restricted access and thus require a longer time for charging than do the lean tissues.

[42] M. F. Morales and R. E. Smith, *Bull. Math. Biophysics*, **6**, 141 (1944).

[43] I. Gersh and M. A. Still, *Naval Med. Research Inst., Research Project X-284, Rept.*, No. III (1944).

3. *Rate of Change of Pressure*

The foregoing facts indicate that complete saturation requires a definite lapse of time, and thus on theoretical grounds alone short deep dives may be effected with less chance of sequelae due to excess inert gas than may long shallow dives. From experience and experimentation the relations of these pressure and time factors have been summarized in diving tables.[44, 45]

The immediate effects limiting the rate of compression are mainly those of a mechanical nature on the ears, sinuses, and other isolated gas phases within the body. Gastrointestinal gases apparently play no role on compression but should be taken into account in view of the ultimate decompression. The effects on the ear and sinuses are not expressible in quantitative form due to the highly individual nature of the response.

The only indication that rapid compression may have some other limiting factor is in the observation of Bean[30] that the influx of gas into the lungs may cause a transient retardation of the CO_2 elimination and thus temporarily elevate the pCO_2 both in the alveoli and blood-tissue complex. Bean found complete arrest of alveolar gas outflow in human subjects during such rapid compression, and reports elevation of pCO_2 in catheterized lungs of dogs under anesthesia.

B. EFFECTS OF MAINTAINED POSITIVE ATMOSPHERIC PRESSURE

1. *State of Saturation of the Several Body Tissues*

The diving tables[45] indicate that saturation at any level is rarely attained in the course of the recommended bottom period since the time schedule for decompression increases throughout with increased stay at the working level. The phenomenally long decompressions necessary for even short stays at great depths prove to be a limiting factor in the amount of useful work that can be effected, even under the best possible conditions; for example, a 20-minute dive of 300 ft. on compressed air requires a total time of 3 hours.

The limitations on the stay at working level are, however, legion. Although electric heating of suits to maintain the body temperature and improvement in construction of the suits to increase mobility and reduce the fatigue of maneuvering the diving rig have been effective in improving the performance of divers, the length of stay at the feasible working depths is still short. The resistance to movement and the difficulty of working against water movements is so telling on the strength of divers that effective work cannot be carried out for the recommended periods except under very favorable conditions of weather and currents.[41]

In caisson work the periods of work are longer in general and as a rule the pressures encountered are limited by the nature of the operations. Pressure depths equivalent to about 100 feet probably are not often encountered and a work period

[44] R. L. Fisher and W. A. White, Jr., *Naval Med. Research Inst.*, Rept. No. 86 (1944).

[45] *Diving Manual, 1943*. Navy Dept., Bureau of Ships, U. S. Government Printing Office, Washington, D. C.

of 1.5 hours twice a day has been used at such levels.[46] Since the conditions for performing useful work are in most cases better for caisson workers than for divers, some difference is understandable. On the other hand, the caisson worker is undoubtedly more nearly saturated than is the diver under these practices and thus more subject to sequelae if proper decompressions are not carried out. It has been the practice in this country for caisson crews to work in divided shifts.[41] The incidence of bends reported by Jones *et al.*[47] is 1.27 per thousand decompressions after a 1.5-hour shift but, due to the reluctance of workers to report mild cases or to have treatment on their own time, there is some question whether complete coverage was obtained. It was found that in tests of prophylaxis, where attention was directed to reporting all cases and where no stigma was attached to such reporting, the incidence was 2.05 per thousand despite the complete lack of any severe cases. Other groups showed incidences of 2.49 and 2.24 per thousand when no treatment or supervision by interested personnel was maintained. The latter higher incidence is undoubtedly related to the extremely casual manner in which decompression is carried out at the insistence of the men themselves.

2. *Effects on the Circulation*

In an academic sense, the blood can carry in physical solution enough oxygen to supply tissue respiration when the inspired partial pressure of oxygen is equivalent to three atmospheres,[48] whereas while breathing one atmosphere of air, less than 1 per cent of the oxygen carried by the blood is in physical solution. The full carrying capacity of the hemoglobin is attained, however, with only slight increase in alveolar pO_2. Therefore, it would seem that oxygen transport per se is more than adequate in compressed air atmospheres.

The situation with regard to CO_2 is by the same token not so favorable. This follows from the fact that the carbon dioxide from the tissues is less readily taken up by the hemoglobin under these conditions and a rise in venous pCO_2 occurs accompanied by a fall in pH with the attainment of the buffer capacity of the blood. Behnke *et al.*[49] showed that the change in pH at 4 atmospheres of oxygen amounted to 0.03 in the venous blood. As indicated above a further temporary enhancement of this effect may follow rapid compression.[50]

In general the pulse pressure and circulation are not uniformly changed by increase in atmospheric pressure, but when very high partial pressures of oxygen are obtained complicating effects from the impaired carbon dioxide transport cause some changes. It is probable that dilation of cerebral and peripheral vessels is effected.[50]

[46] *Occupation and Health.* International Labor Office, Geneva, 1930.

[47] R. R. Jones, J. W. Crosson, F. E. Griffith, R. R. Sayers, H. H. Schrenk, and E. Levy, *J. Ind. Hyg. Toxicol.*, **22**, 427 (1940).

[48] A. R. Behnke, *Bull. New York Acad. Med.*, **18**, 561 (1942).

[49] A. R. Behnke, L. A. Shaw, C. W. Shilling, R. M. Thompson, and A. C. Messer, *Am. J. Physiol.*, **107**, 13 (1934).

[50] J. W. Bean, *Physiol, Revs.*, **25**, 1 (1945).

3. *Oxygen Poisoning*

At from 3 to 4 atm. of oxygen, or corresponding oxygen pressure in air, certain motor disturbances of cerebrocortical origin develop. The syndrome is called "oxygen poisoning" and may show only minor twitches but usually progresses to full-blown convulsions within a short time. This is an acute condition related qualitatively to symptoms known to affect individuals maintained at a partial pressure of oxygen above about 600 mm. Hg for periods of several days.[51] The primary effects at normal atmospheric pressure seem to be a pulmonary involvement resulting in substernal distress and coughing with a clinical picture of lung congestion, while the acute conditions brought on by exposure to high partial pressures of oxygen over short intervals at increased atmospheric pressures affect the central nervous system, causing seizures, loss of consciousness, narrowing of the visual fields through scotomata, and so forth, which overshadow the appearance of less spectacular symptoms. The modus operandi of oxygen poisoning is in considerable dispute at the present time since both CO_2 and O_2 are known to have destructive effects on isolated systems at increased pressure.[50] Recent studies tend to show that irreversible or incompletely reversible changes take place in all intracellular reactions and particularly in the central nervous system, and there is good reason to believe that the normal gas-handling systems involving enzymes are intimately affected.[50]

4. *Inert Gas Effects*

From the experimental work on deep-sea diving and salvage it was reported by Behnke and Yarbrough[52] and Case and Haldane[53] that helium reduced the severity of a syndrome that attends exposure to high pressure atmospheres, about 10 atmospheres, even though oxygen tensions were maintained at the normal level. This work resulted from an attempt to find a diluent for oxygen less soluble than nitrogen. According to Behnke and Yarbrough[52] argon and nitrogen have a narcotic effect at high atmospheric pressures that is proportional to the molecular weight and oil/water solubility ratio. Bean[50] feels that the narcotic symptoms can be ascribed to a more understandable mechanism involving carbon dioxide accumulation even though it is transient, and that the effects of the different inert gases are exerted on the transfer of the carbon dioxide rather than directly in some way on the metabolic processes. It is difficult to assess these two approaches because of the lack of quantitative criteria and adequate data, but although the carbon dioxide theory has an apparent simplicity in its favor, the correlation between the narcotic responses of the inert gases and their oil/water solubility ratios, as is true for narcotic substances, generally, and the common property of a lack of active chemical effects lend substance to the claims of Behnke.

[51] H. Becker-Freyseng and H. G. Clamann, *Luftfahrtmedizin*, **7**, 272 (1942).
[52] A. R. Behnke and O. D. Yarbrough, *Am. J. Physiol.*, **126**, 409 (1939).
[53] E. M. Case and J. B. S. Haldane, *J. Hyg.*, **41**, 225 (1941).

5. *Effects of Temperature and Humidity*

At the pressures existing in most caisson installations the incidence of disturbances during maintained pressure is very low, but nevertheless after long exposures some prostrations have been reported. At the level of pressure existing in these instances there is no reason to expect "oxygen poisoning" and it has been impossible to show such effects in experimental work on animals in compressed air.[54] Disorientation, epileptiform seizures, and painful cramps of the arms and legs seem to be the most marked symptoms and are not readily differentiable from the syndrome appearing after decompression. There is thus some evidence that with complete saturation at even moderate pressures disturbances of central origin may be expected. It is possible that in actual practice other factors such as heat and humidity play a role not fully recognized because the attention of investigators is drawn by the hazards of compressed air as discussed elsewhere.

The effects of temperature during positive pressure work shifts are similar to those at normal atmospheric pressure except for qualitative differences brought about by the fact that humidity values are always high, and the normal modes of heat loss are thus restricted to radiation and convection. Temperatures of 90.0° F. are often encountered in caisson work because of the lack of heat exchangers between the compressors and the inlet ports to the caisson and the exposed situation of some equipment. In such an environment prostration due to excessive sweating and circulatory disorders are bound to occur. In the event that these reactions are subclinical but followed by uncritical decompression they may act as predisposing factors for the sequelae of bends and more severe responses. In all caisson work ventilation is effected in one way or another and there are minimum rates set up by local authority that are designed to prevent the accumulation of CO_2 respired by the workers.[41] In general this ventilation does not serve to lower the temperature of the caisson.

6. *Other Effects and Subjective Responses*

Subjectively, the attainment of positive pressure levels seems to result in an exhilaration or euphoria, which has been thought to be reflected in an increased capacity for muscular work,[54] but the effect soon gives way to a depressed state. Disturbances of the senses of smell and taste may appear. Alterations of the voice are a constant feature of speech in compressed-air atmospheres. The explanation for this phenomenon has not been established, despite attempts to show that density and its effects on the resonance chambers of the head and chest produce similar changes. The same changes and difficulties of speech, nasal high-pitched sounds, and straining of the muscles of the larynx, can be elicited at normal pressure when breathing oxygen mixtures containing hydrogen or helium and no change back to the normal tone can be effected by increasing the absolute pressure of such mixtures. As far as can be ascertained these changes due to compressed air are strictly reversi-

[54] H. Gerbis and R. Koenig, *Drucklufterkrankungen*. Thieme, Leipzig, 1939.

ble except perhaps for the soreness of the laryngeal surfaces and muscles produced by straining.

C. DISCHARGE OF GASES FROM THE BODY FOLLOWING EXPOSURE TO INCREASED ATMOSPHERIC PRESSURE: DECOMPRESSION

1. *Mechanical Effects*

The mechanical effects of decreasing the pressure of the gases surrounding the body may be arbitrarily limited to the condition that a discrete gas phase already be present, e.g., in the middle ear, intestinal gases, etc. Although there is no question that gases freed from solution do exert a mechanical effect both extra- and intravascularly, the latter will be considered separately.

In the middle ear there is usually no serious effect unless complete closure of the eustachian tube has occurred. Since this condition would have precluded entrance to positive pressure the incidence of middle ear troubles is low. The same applies to the effects on the sinuses, and even though some blockage may occur the pains that develop are mainly from displacement of the tissues and ischemia of the mucous linings, and are relatively minor. It is possible that movement of the round window separating middle and inner ear lumens may permit injection and hemorrhage of the capillaries in the inner ear. This eventuality has a more serious prognosis than similar trauma in the middle ear because it may result in scarring of the receptor tissues of the cochlea and consequent deafness to various frequencies of sound.

The expansion of intestinal gases is a potential hazard in decompression although little mention of it is made in the literature. This is perhaps due to the fact that in caisson and diving work elimination of flatus is generally accomplished before the shift is over and also to the indoctrination of workers in dietary regimes that avoid gas-producing food. In any event the presence of intestinal gas during rapid decompression will cause discomfort only in proportion to the expansion ratio effected in the routine followed. Since in most cases this involves the Haldane or Bornstein stage method of decompressing to half the starting pressure,[54, 55] the expansion will be some two times (greater by the effect of water vapor[56]) the volume at equilibrium. In most cases this is a moderate stimulus to the smooth muscles of the gastrointestinal tract and results in the expulsion of the gas.

A more serious consequence of mechanical nature is the rupture of the lungs during even moderate decompressions because of the failure to keep the respiratory passages open.[57] This rupture occurs mainly in cases of sudmarine escape where a tendency to hold the breath is the natural result of apprehension nad unfamiliarity with the unusual environment. The incidence in caisson workers and divers is undetermined, but the individual should be warned against breath holding during decompression.

[55] J. S. Haldane and J. G. Priestly, *Respiration*. Yale Univ. Press, New Haven, 1935.
[56] C. H. Fugitt, *U. S. Naval Air Training Bases, Pensacola, Fla., Project X-579, Rept.* No. I (1945).
[57] I. B. Polak and B. H. Adams, *U. S. Naval Med. Bull.*, **30**, 165 (1932).

2. Bubble Formation

The rate of removal of a gas from a fluid must keep pace with the tendency to desaturation resulting from a fall in total pressure if the formation of a free gas phase, i.e. bubbles, is to be prevented. The physiology of bubble formation may be best evaluated by a consideration of the mechanism based on the kinetic theory of gases. The molecules of a liquid may exist in the gaseous state, and while in the gaseous state they have a higher average energy content than their fellows in the liquid state. Presumably then, the average energy of gas molecules dissolved in a liquid composed of other molecules becomes equal to the average energy of the liquid molecules. A bubble of gas will not form unless sufficient energy is applied to enough gas molecules in a restricted locus to result in displacement of the liquid molecules. The chances for the spontaneous localization of such energy quantities are very slight and it is generally assumed that minute gas or vapor spaces large enough to permit initiation of bubbles are always present at liquid–solid interfaces under natural circumstances.[58–60] These spaces have been termed "gas nuclei." (Harvey[61] has been instrumental in popularizing this term, but it is probably less confusing to call the spaces *bubble nuclei.*)

The data gathered from many experiments on degassing by Kuper,[58] Piccard,[59] Harvey *et al.*,[62] and Dean[60] indicate that a free-gas phase forms readily only if a space is present into which the gas may diffuse. Relatively enormous supersaturations are possible in the absence of such bubble nuclei. It is probable that under normal life conditions nuclei exist in profusion, specifically at such points as on substances active in the transfer of gases, such as hemoglobin and other respiratory pigments. The question of the ultimate locus of bubble formation is one that is being actively investigated at this time, and until definitive evidence is at hand no further analysis can profitably be made.

From the work of Gersh[63] it is indicated that a gross correlation of the distribution of bubbles with that of fat tissues is found in decompressions from positive pressure. It seems that these loci by virtue of their relatively high gas content have at least the requisite condition for maintaining patent bubbles whether or not they offer the highest incidence of nuclei among the various tissues of the body. In point of time it is evident, however, from these data that bubbles in the vessels appear in greater number than bubbles in fat, at least in the early stages of this condition.

The evolution of gases from solution in the various tissues of the body on decompression gives rise to the main body of sequelae and forms the basis of the

[58] J. B. H. Kuper, *Rept., Aviation Medicine Unit, Ind. Hyg. Research Lab., Natl. Inst. Health*, Bethesda, Md. (1942).

[59] J. Piccard, *Proc. Staff Meetings Mayo Clinic*, **16**, 700 (1941).

[60] R. B. Dean, *J. Applied Physics*, **15**, 446 (1944).

[61] E. N. Harvey, A. H. Whitely, W. D. McElroy, D. C. Pease, and D. K. Barnes, *J. Cellular Comp. Physiol.*, **24**, 23 (1944).

[62] E. N. Harvey, D. K. Barnes, W. D. McElroy, A. H. Whitely, D. C. Pease, and K. W. Cooper, *J. Cellular Comp. Physiol.* **24**, 1 (1944).

[63] I. Gersh, G. E. Hawkinson, and E. H. Jenney, *Naval Med. Research Inst., Research Project X-284, Rept.* No. V (1944). Also in *J. Cellular Comp. Physiol.*, **26**, 63 (1945).

occupational disease of workers in compressed-air atmospheres. The essential facts are that on decompression the body fluids are supersaturated to a varying degree depending on the pressure attained and the time of exposure. If the supersaturation is great enough in the face of a continuous loss of the gas through circulation and respiration, then discrete gas phases will form, both intra- and extravascularly. These accumulations of gas then act to disturb the normal functions of the tissues in which they appear in proportion to their number and size. Thus, in the vascular system bubbles are found to form largely in the venous vessels and they are carried to the right heart and lungs where they accumulate and are responsible for the symptoms known as the "chokes."[64] This is a disability of varying degree, depending upon the extent to which the circulation of the lungs is interfered with. In general, it is considered a serious condition and recompression is instituted as quickly as possible. The appearance of bubbles in the blood is usually accompanied by appearance of bubbles in the various tissues, the fatty tissues being most subject to bubble formation.[65, 65a] While the cause of the symptoms of "bends" and other peripheral symptoms such as pruritus, tingling sensations, joint and tendon pain, is still a moot point there is little doubt that the presence of the bubbles constitutes one of the most reasonable mechanisms for the development of local ischemia in the tissues, particularly in the skin. End[66] and Swindle[67] indicate that intravascular bubbles may be secondary to the embolism caused by the agglutination of red cells following exposure to compressed air, but confirmation of this effect is lacking. In many instances, however, nonsymptomatic accumulations of gas are found in large quantity, as for instance in the fascial layers beneath the skin and between the muscles. They produce a crepitation during manipulation. The question of whether intra- or extravascular bubbles are responsible for such occlusions is an academic point, but one from which future prophylactic measures will evolve.

Given the general mechanism of occlusion or embolism the whole gamut of symptoms presented by decompression sickness can be seen to have a common cause. In particular, the effects of central nervous system disorganization and breakdown are directly traceable to the anoxia of motor centers and the integrating mechanism of the cortex and medulla. Thus the reported "monoplegia, paraplegia, Ménière's complex, apoplectic deafness, vertigo, aphasia, hemiplegia, etc." are all manifestations of this basic mechanism, throughout the nervous system. In fact, the cause of death in the majority of cases is rather to be attributed to a cerebral embolic accident than to general anoxia from cardiac failure or a toxic effect of the exposure on the tissues.[54, 64]

The statistical distribution of symptoms of caisson disease indicates that

[64] I. Gersh, *Naval Med. Research Inst., Research Project X-284, Rept.* No. X (1945). Also in *J. Cellular Comp. Physiol.*, **26**, 101 (1945).

[65] I. Gersh, G. E. Hawkinson, E. N. Rathbun, and A. R. Behnke, *Naval Med. Research Inst., Research Project X-284, Rept.* No. II (1944). Also in *J. Cellular Comp. Physiol.*, **24**, 35 (1944).

[65a] I. Gersh, *Naval Med. Research Inst., Research Project X-284, Rept.* No. IX (1945). C. E. Wagner, *ibid., Rept.* No. IV (1944).

[66] E. End, *J. Ind. Hyg. Toxicol.*, **20**, 511 (1938).

[67] P. F. Swindle, *Am. J. Physiol.*, **120**, 59 (1937).

peripheral effects predominate.[54] This may be related to the fact that peripheral reservoirs of fat unload their nitrogen slowly and therefore are subject to bubble formation, while only in case of gross supersaturation of the individual will chokes and central nervous system disturbances appear.

It is possible that the caliber of the vessels in the lungs and the brain play some part in this distribution, since it is generally estimated that the capillaries are larger here than in other tissues; thus only when large bubbles form either directly or by fusion from smaller bubbles will effects in these regions be expected.

3. Rate of Decompression

The problem of desaturating the tissues without causing bubble formation has been recognized since Bert's researches.[68] The first attempts to circumvent this phenomenon were not very successful and were extremely time-consuming because it was thought that uniform, slow decompression would prevent bubbles from being initiated. This procedure, however, resulted in maintaining such a low differential pressure across the interface between tissue and environment that transfer of gas was slow, and bubbles formed despite all precautions. Haldane[55] then instituted the technique of decompressing rapidly to such a pressure as to create a large differential pressure between tissues and environment but still small enough to prevent bubble formation in the time used for desaturation. After desaturating at this level for an appropriate period the pressure was again reduced and a somewhat longer period of desaturation followed. By extension this procedure will bring the diver to the surface in considerably less time than with the former method and without as great a hazard. It was shown experimentally that the pressure could be safely reduced to one half at each stage, and the period of desaturation was calculated from composite data on the different rates of desaturation of various tissues of the body.

The method outlined above is essentially the one in use in all decompression procedures but certain minor innovations have been applied by subsequent experimenters.[69] The Continental practice is a similar modification introduced by Bornstein,[54] in which the initial rapid reduction in pressure is made as in Haldane's method, but subsequently a continuous slow ascent is made. This method, according to its originator, maintains the gradient of pressure effected by the initial pressure drop throughout the decompression and further reduces the total decompression time.

The diving tables in use in this country are constructed on the stage basis of Haldane but include an ascent between stages of not more than 25 feet per minute.[70] Acceleration of the ascent schedule has been effected by the introduction of ventilative breathing of pure oxygen at the later stages when the total pressure is low enough to avoid effects of oxygen poisoning, but for economic reasons this method is used only in decompressions after recompression following bends or other serious

[68] P. Bert, *La pression barométrique*. Available in English as *Barometric Pressure*, M. A. and F. A. Hitchcock, trans., College Book Co., Columbus, Ohio, 1943.

[69] A. E. Boycott, G. C. C. Damant, and J. S. Haldane, *J. Hyg.*, **8**, 342 (1908).

[70] Anon., *Diving Manual, 1943*. Navy Dept., Bureau of Ships, U. S. Government Printing Office, Washington, D. C.

decompression symptoms.[71] The use of helium in place of nitrogen has been advocated because of its lower solubility, but its principal contribution is the elimination of "nitrogen narcosis" in deep diving.[66, 67, 72, 73, 73a]

The practice in decompression for caisson workers is a continuous slow reduction to one half the working pressure. Attempts to decrease bends incidence by oxygen breathing have been made with some success.[74] Uniform decompression rates have been prescribed by law[75] in the past but changes in the codes have been made to take advantage of more rapid methods, with due consideration for safety. In many instances there is an over-all limitation in the minimum period for decompression without strict interpretation of the initial rate of pressure reduction. Because of marked fog formation in this practice, and the lowering of the decompression chamber temperature during this procedure, serious consideration is given in Continental codes[54] to moderate recompressions following each stage of decompression, in order to warm the air slightly and thus avoid chilling the men who have been at hard work in a hot and humid atmosphere. The reasons for this practice are derived from the fact that peripheral circulation is practically occluded by vasomotor response to lowering of the temperature, and thus desaturation of the skin and adjacent tissues is prevented, with the unpleasant results of bends, itching, and similar sequelae.

As suggested above, the desaturation procedures described here do not proceed without occasional symptoms of decompression sickness, and this debility may appear for some hours after decompression because of bubbles from nitrogen reservoirs not properly desaturated. The subsequent lodgment of such bubbles in a critical point of the circulation will bring about the same symptoms as mentioned above and in the same range of severity. Thus, it is necessary to keep decompressed individuals within reach of recompression equipment and to apply pressure and ventilative breathing of oxygen until remission of symptoms is complete.[71] The re-solution of bubbles is slow at recompression conditions due to the decreased bubble surface presented during recompression.[58] Unfortunately, these procedures often have been carried out on the worker's time, thus introducing a deterrent factor and therefore many cases have been prolonged unnecessarily. In large part, the blame for poor decompression technique falls on the workers themselves since they are often reckless in their haste to decompress and get off the job; and many have the ill-conceived notion that they have tough constitutions which will enable them to absorb such abrupt changes without permanent effects.[74]

Repeated exposure to bends symptoms, and perhaps even the mere repetition

[71] O. E. Van der Aue, W. A. White, Jr., R. Hayter, E. S. Brinton, R. J. Keller, and A. R. Behnke, *Experimental Diving Unit, Navy Yard (Washington, D. C.) and Naval Med. Research Center (Bethesda, Md.), Research Project X-443, Rept.* No. I (1945).

[72] E. D. D. Dickson, J. E. G. McGibbon, and A. C. P. Campbell, *J. Laryng. Otol.*, **58**, 465 (1943).

[73] A. R. Behnke, R. M. Thomson, E. P. Motley, *Am. J. Physiol.*, **112**, 554 (1935).

[73a] E. End, *Am. J. Physiol.*, **120**, 712 (1937).

[74] R. R. Jones, J. W. Crosson, F. E. Griffith, R. R. Sayers, H. H. Schrenk, and E. Levy, *J. Ind. Hyg. Toxicol.*, **22**, 427 (1940).

[75] *Occupation and Health.* International Labor Office, Geneva, 1930.

of decompression without discernible symptoms, will in time produce effects in those regions where bubble formation usually takes place.[54] In general, these chronic lesions are situated in the joints and in other tissues with poor circulation. They are thought to be the result of bubble trauma and repeated acute, or chronic, low-grade anoxia of the local tissues. They include: simulated arthritic effects of hip and knee joints, ankylosis of the incus, malleus, and stapes of the middle ear, thickening of the drum, and so forth.[54]

IV. Effects of Reduced Atmospheric Pressure on the Body

Ascent into the atmosphere simulates physically the conditions attending decompression from increased atmospheric pressures. It will be seen, however, that the ratio of pressure change permissible for the diver cannot be attained by the aviator. Thus, divers can work at 10 atm., a ninefold difference from their natural environment, yet at 1/2 atm. there is serious disturbance for the aviator, and few, even hardened and acclimated, men have ever attained 1/3 atm. for more than passing intervals.[76] The difference in range is mainly due to the fact that the decrease in barometric pressure on ascent to altitude strikes at the only component of the body's energy-liberating mechanism that it is unable to store to any reasonable extent: oxygen. The following sections will deal with this and other limiting factors in a manner comparable to that of the preceding section on positive pressures.

A. DISCHARGE OF GASES FROM THE BODY: DECOMPRESSION

As in decompression from positive pressures, the reduction in environmental pressure causes a differential pressure to exist between the gases dissolved in the body and the ambient atmosphere. In this case, however, the body is usually in complete equilibrium with the inert gases and thus will be supersaturated as soon as any ascent is begun. Obviously, the body will lose part of all the gases dissolved in it, even oxygen if the rate of ascent is abrupt enough, and this efflux of gases is regulated by the access that the various parts of the body have to the exterior. Thus, the fatty tissues and those with poor vascularization will maintain a high differential pressure as compared with others more favorably endowed.

1. *Rate of Ascent*

At the present writing, the physical possibilities of rates of ascent can hardly be overestimated. Given a suitable initial change of acceleration, the practical limitations for the newer type of aircraft are actually beyond the capacity of the body for coping with the changes in the environment; for example, the little defensive rocket-propelled "viper" developed by the Germans for use against Allied bombers made a practically vertical ascent to over 30,000 ft. in somewhat less than two minutes, and it is probable that this is not the maximum that can be attained for piloted aircraft. In any case, this rate of ascent induces a pressure differential of nitrogen of about 368 mm. Hg in a matter of minutes, discounting for the moment the loss of nitrogen in this time from some of the tissues. Thus, as will be seen below, ascents can be

[76] S. Ruff and H. Strughold. *Grundrisse der Flugfahrtmedizin.* Barth, Leipzig, 1939.

made in such time intervals that the normal routes of gas transfer cannot handle the amount of gas that tends to be freed from solution.

Catchpole and Gersh[77] have shown that for rabbits the critical rate of ascent lies somewhere near 7000 to 8000 f.p.m., even though the animals are breathing oxygen during ascent. At 4500 f.p.m., survival at 45,000 ft. for 30 minutes indicated that serious effects were not incurred at this rate. In human decompressions to altitude more conservative estimates must be made, first, because of the difference in size and vascularization as compared with those of small mammals, and, secondly, because of factors other than bubble formation. In decompression for experimental purposes where bends are to be avoided it has been the practice to ascend at about 2000 to 3000 f.p.m. In indoctrination ascents for fliers, the rate of ascent has been set as high as 5000 f.p.m. In the latter case, bends do occur in some instances and this routine has been used to assist in selection of air crews. The experience of the Army Air Corps[78] shows that ascent at maximum feasible rates of climb, about 5000 f.p.m., at the time of this writing produces a bends syndrome only above 18,000 ft. and the severity is dependent on contributing factors of exercise, cold, length of stay, and so forth.

Of more fundamental nature is the relation of rate of ascent to the absolute pressure levels attained during ascent. That is, the partial pressure of oxygen during ascent falls, and ultimately a point is reached at which the saturation of the hemoglobin of the blood can no longer be effected. This level is generally defined as about 10,000 ft., since the first disturbances to psychomotor responses become measurable at this level. Thus, the rate of ascent determines the point in time at which the individual arrives at the critical levels. In the case of rapid ascent cited earlier, advantage was taken of even the limited storage that the body can effect for oxygen, that is, the reserve time or asphyxiation time, in that the discharge of the pilot's duties needed to be effected over only a period of minutes, and for this interval his oxygen reserve could be made to suffice. It is doubtful that such close figuring will be resorted to in the future unless it becomes a matter of desperation.

In general the influence of rate of ascent can be obviated by the simple procedure of breathing oxygen from a mask, beginning before ascent to remove body nitrogen,[78a] and continuing during ascent to prevent desaturation of the hemoglobin of the blood. This expedient raises the critical level to about 40,000 ft. at which point the absolute pressure just suffices to maintain proper saturation of the hemoglobin of the blood. To obtain independence of these factors it is necessary to maintain a pressure differential between the individual and his altitude environment. Various methods have been devised, but pressurization of cabins in aircraft seems to be the most suitable one.[79]

[77] H. R. Catchpole and I. Gersh, *Naval Med. Research Inst., Research Project X-284, Rept.* No. VI (1945). Also in *J. Cellular Comp. Physiol.*, **27**, 15 (1946).

[78] *War Dept., Tech. Manual* 1–705 (1941).

[78a] A. H. Whitely, W. D. McElroy, G. H. Warren, and E. N. Harvey, *J. Cellular Comp. Physiol.*, **24**, 257 (1944).

[79] Aero Medical Laboratory Staff, *AAF Manual* No. 25–2 (March, 1945).

2. Evolution of Gases from Solution in Body Tissues during Ascent

It has been shown empirically that, although rate of ascent has some influence on the incidence of decompression sickness, there is a delay in the onset of symptoms that is inversely related to the altitude attained. This correlates with the fact that bubbles must have a period of growth, either by diffusion of gas or by coalescence, before they become effective. This delay is usually long enough so that no symptoms appear during ascent to altitudes below 45,000 ft. The reasons for this delay are not known precisely, but it is apparent that, whatever the cause of the initial delay, the failure of bends to appear in slow ascents with oxygen breathing is most probably due to the relatively good inert-gas elimination attained.

It is known from diving practice and experimental work[80] that decompression from two atmospheres absolute can be carried out without risk of bends by rapid decompression to one atmosphere under normal conditions, and this ratio of pressures was shown to preclude bubble formation at any feasible level of absolute pressure. Recent work[81, 81a] indicates that abnormal conditions of activity may decrease the ratio markedly. However extension of this rule to reduced pressures is justified empirically since reports of bends or chokes from decompression to reduced pressure have not been made below 26,000 ft., or about 1/3 of an atmosphere.[82, 83] In justice to the facts it must be added that human exposures to reduced pressure at such levels were nearly always carried out with added oxygen, although there was in such instances an appreciable partial pressure of nitrogen in the respired air.[78] When animals are exposed to reduced pressure, bubbles are rarely found after exposure to pressure–altitude equivalents under 15,000 ft.,[84] even with the most extreme conditions of muscular stress. On the other hand, in resting animals this critical level is equal to or above that found for man, depending to some extent on the body size of test animals. The physical reasons for the lack of bubble formation with saturations below a critical level are not well understood but it can be shown that *in vitro* the lack of properly dimensioned bubble nuclei will prevent bubble formation until the differential pressure has reached a definite level,[62, 84a] and that at each new level of pressure a new crop of bubbles arises from nuclei that were ineffective at lower differential pressures. It is therefore inferred that the lack of suitable bubble nuclei in the body is one of the limiting factors that allow such high supersaturations to exist without symptoms of decompression sickness.

[80] J. S. Haldane and J. G. Priestley, *Respiration.* Yale Univ. Press, New Haven, 1935.

[81] M. Harris, W. E. Berg, D. M. Whitaker, V. C. Twitty, *J. Gen. Physiol.*, **28**, 241 (1945).

[81a] E. N. Harvey, W. D. McElroy, A. H. Whitely, G. H. Warren, and D. C. Pease, *J. Cellular Comp. Physiol.*, **24**, 117 (1944). W. D. McElroy, A. H. Whitely, G. H. Warren, and E. N. Harvey, *ibid.*, **24**, 133 (1944). W. D. McElroy, A. H. Whitely, K. W. Cooper, D. C. Pease, G. H. Warren, and E. N. Harvey, *ibid.*, **24**, 273 (1944).

[82] R. A. Kritzler, *War Med.*, **6**, 369 (1944).

[83] H. A. Smedal and E. B. Brown, *U. S. Naval Air Training Bases, Pensacola, Fla., Project X-609. Rept.* No. 1 (1945).

[84] M. Harris, W. E. Berg, D. M. Whitaker, V. C. Twitty, and L. R. Blinks, *J. Gen. Physiol.*, **28**, 225 (1945).

[84a] W. E. Berg, M. Harris, D. M. Whitaker, and V. C. Twitty, *J. Gen. Physiol.*, **28**, 253 (1945).

3. *Mechanical Effects*

The mechanical effects of decompression to altitude are identical with those obtaining on decompression from high-pressure atmospheres. In general there are minor symptoms only, and these arise from the pressure exerted by entrapped air when the atmospheric pressure falls. The pressure exerted internally in the middle ear usually falls off readily by displacement of the air through the eustachean tube, and a similar discharge from the sinus spaces takes place unless congestion from colds or other inflammations closes off the openings into the nasopharynx. With such closure, a fall in atmospheric pressure will allow the internal gases to displace the blood from the tissues lining the space, and this ischemia plus displacement of the yielding portions of the space will cause a varying degree of pain. The mechanics of the openings to these spaces lends itself so well to relief of internal pressure that only with the most serious cases will more than fleeting sensations be experienced.[81b]

On the other hand, there is a more drastic effect to be expected from the expansion of the gases in the gastrointestinal tract. As in the case of decompression from high atmospheric pressures, there is expansion, but the effect caused by water vapor is considerably exaggerated. This is due to the fact that the vapor pressure of water is constant with the temperature of the body and, since it is an increasingly larger part of the total pressure, as ascent is made it causes an increasingly larger distension of the soft-walled gas pockets.[85] Thus, a decompression from 10 atm. to 1 causes a volume increase of water-saturated air from 1 to 10.59, or a gain of a little more than half a volume over the dry expansion; while a decompression from 1 atm. to 1/10 atm. would result in a wet volume increase of 24.6 times, or a gain of 14.6 volumes over the dry expansion. Even at 1/5 atm., 38,500 ft., there is a volume increase of 6.66 times rather than the fivefold dry expansion from one atmosphere. These considerations form the basis of the observation that at moderate altitudes flatus expansion can be readily handled by the normally induced movements of the smooth muscle of the gastrointestinal tract, but at an altitude of 30,000 ft. or above the tendency of the smooth muscle to give way to gradually increasing internal pressures results in meteorism with all its attendant symptoms.

Besides the excruciating pain caused by these effects there is in addition a restriction of the movement of the diaphragm and thus a respiratory embarrassment. In any case, the prophylaxis of avoiding gas-forming foods and the treatment of early symptoms by massage and movement of the abdomen are soon put into practice by the individual who has the misfortune to experience this distress. According to an extensive series of uniformly conducted indoctrination ascents for Army airmen, Swann and Rosenthal[86] reported an incidence of gas pains severe enough to

[81b] O. E. Reynolds, H. C. Hutchins, A. Y. Werner, and F. R. Philbrook, *U. S. Naval Med Bull.*, **46**, 845 (1946).

[85] C. H. Fugit, *U. S. Naval Air Training Bases, Fla., Project X-579, Rept.* No. I, 1945.

[86] H. G. Swann and T. B. Rosenthal, *A Survey of the Incidence of Decompression Sickness With Reference to Some Constitutional and Environmental Variants.* AAF School of Aviation Med., Randolph Field, Texas.

cause descent of 0.59 per cent; of these, less than 15 per cent occurred during ascent to 30,000 ft.; 73 per cent occurred after arrival at the working level of 38,000 ft.

The most critical conditions for mechanical effects from decompression arise in the situation in which explosive decompression from pressurized cabins occurs. Under these conditions a volume change theoretically as great as 2.3 times the original volume was experienced in laboratory tests in 0.008 second without detectable harm. It is probable that the displacement of lung gases proceded as indicated but the expansion of intestinal gases, if any, was somewhat less due to the tone of the muscles. Cabin pressurization, for the reasons discussed above, is decreased at great altitudes because of the lack of a margin of safety in the rate of decompression.[79] Breath holding is an obvious hazard which, although it has not occurred in these tests, might result in pulmonary emphysema, as in the submarine escape conditions cited earlier.[87]

B. THE EFFECTS OF MAINTAINED LOW ATMOSPHERIC PRESSURE

1. Hypoxia

It is evident from the previous treatment of the physical nature of reduction of barometric pressure that the partial pressure of oxygen falls in direct proportion to that of the total pressure. Thus an ascent to 1/2 an atmosphere pressure will result in an ambient partial pressure of oxygen equal to 79.5 mm. Hg. From Figure 4 it is seen that the theoretical saturation of the blood with oxygen might be as great as 95 per cent if this were the actual partial pressure of oxygen at the lung capillaries. Owing to the fact that gaseous exchange takes place within the depths of the lungs, and because there is never a complete exchange of the contained gases of the lungs, the partial pressure of oxygen is subject to several factors that bring about a reduction in its magnitude. The first is a matter of dilution with the residual gases in the lungs and their large air passages; the second is an addition of water vapor to the air from the moist surfaces of the lungs. The former is a structural factor that varies from one individual to another; the latter varies only with the temperature of the evaporating surface within the lung. It becomes apparent now that the water vapor is a sort of constant that we must arbitrarily deduct from the total barometric pressure in order to find the effective pressure and that, moreover, it becomes a larger and larger part of the total pressure as we ascend. At 1/2 atmosphere, by analysis[79] the composition of the gases nearest the circulating blood, the so-called alveolar gas, has an oxygen partial pressure of only 36 mm. Hg, which would result in a saturation of the arterial blood of less than 70 per cent. It is this reduction in the saturation of the blood that is the primary factor in the disturbances attendant to ascent to high altitudes, since it interferes with the adequate transport of oxygen to the tissues, particularly those of the central nervous system that have the highest rate of metabolism and the smallest reserve.[76, 79]

The reduction in partial pressure of the oxygen in the blood will excite the reflex mechanism of the carotid artery bulb, which excitation effects an increase in the

[87] I. B. Polak and B. H. Adams, *U. S. Naval Med. Bull.*, **30**, 165 (1932).

rate of ventilation of the lungs, resulting in the removal of carbon dioxide (and perhaps some water vapor), with moderate improvement in the partial pressure of the oxygen in the lungs. While this response to lowered oxygen pressure in the blood is purposeful at normal atmospheric pressure, it is rarely called upon and less effective than a parallel mechanism of the respiratory center in the medulla. The latter responds to the increase in carbon dioxide that ordinarily follows oxygen depletion in the body from muscular exertion. This mechanism is, however, also responsive to a decrement in the partial pressure of carbon dioxide, and to the exclusion of excitations of the carotid bulb mechanism due to reduced oxygen pressures in the circulating blood. At altitude, therefore, a dilemma soon arises. Ventilation increases in response to the lowered oxygen pressure. This washes out carbon dioxide from the lungs and blood, with the result that ventilation falls off again. Thus a vicious cycle of fluctuating respiration sets in, with a progressive drop in oxygen pressure and saturation of the blood until central nervous system metabolism is so depressed that dysfunction and failure occur. Cyclic respiration has been described frequently as an early symptom of mountain sickness and is symptomatically equivalent to Cheyne-Stokes breathing. At intermediate altitudes, breathing air, and at equivalent altitudes breathing oxygen, it is observed that equilibria in respiration may be attained by normal individuals in such a manner that effective ventilation for oxygenation may be maintained by the adjustment of CO_2 levels in the blood and accommodation of the respiratory centers to this altered milieu. A concise exposition of alveolar gases and ventilation phenomena has been formulated by Fenn, Rahn, and Otis[87a] with numerous charts illustrating the effects of different levels of altitude. In practice this information may be applied industrially at high terrestrial altitudes, as for example in mining, etc., but the use of pressurization and supplementary oxygen in commercial aviation makes it necessary for consideration only in emergencies.

While the acute response to oxygen lack may be unconsciousness and ultimate death, the more chronic exposure to low-grade hypoxia may produce a variable response ranging from inefficiency in both muscular control and mental processes to disturbances of central nervous system structures, inducing a neurocirculatory collapse, or at higher altitudes a peripheral circulatory collapse, which results in a state of shock with its attendant progressive deterioration.[76, 79] It is probable that nearly all these derangements have a common mechanism rooted in nerve-tissue hypoxia,[88] but the variable responses that can be elicited from such a complex structure take on such a confusing aspect that analysis to a single cause is not practicable.[88a]

2. Hypocapnia

As suggested above, the partial pressure of carbon dioxide undergoes changes at altitude as a secondary response to the hypoxia. Its effects are, nevertheless, quite

[87a] W. O. Fenn, H. Rahn, and A. B. Otis, *Am. J. Physiol.*, **146**, 637 (1946).

[88] W. P. Yant, J. Chornyak, H. H. Schrenk, F. A. Patty, and R. R. Sayers, *U. S. Pub. Health Bull.* No. **211** (1934).

[88a] G. A. Brown, C. L. Cronick, H. L. Motley, E. J. Kocur, and W. O. Klingman, *War Med.*, **7**, 157 (1945).

marked and unfortunately unadapted to the circumstances. The loss of carbon dioxide from the blood can be seen from Figure 4 to cause more oxygen to be combined with hemoglobin at the same pressure of oxygen than before such a depletion. While this may at first seem to be satisfactory in increasing the transport of oxygen, it will be effective in the tissues only if the carbon dioxide pressure is maintained or raised through increased metabolism. The hemoglobin will have a correspondingly increased affinity for oxygen in the capillaries if the pressure of carbon dioxide is decreased there as in the lungs. Unfortunately, the conditions that cause the hypoxia are not metabolic and thus carbon dioxide partial pressure falls throughout the body. This falling of the pressure brings on the depression in ventilation discussed above, and also a train of other effects characteristic of this condition.[79] Thus, hypocapnia brings on peripheral sensory disturbances described as a tingling, especially of the hands, apprehension and other subtle psychological changes which are precursors of a more drastic central nervous system response, often inducing strong autonomic stimulations resulting in vomiting. The latter is particularly hazardous in aviation because the presence of a mask will result in aspiration of the vomitus and complete asphyxia unless immediate aid is rendered.[76]

If the hypoxia caused by breathing ambient air at altitude is avoided by breathing oxygen then normal carbon dioxide pressures will be maintained, but as higher altitudes are reached the internal maintenance of carbon dioxide pressure through metabolic activity imposes a growing restriction that has been suggested previously, that is, the partial pressure of carbon dioxide tends to remain constant and thus becomes a larger and larger part of the total pressure and in effect prevents the entrance of sufficient oxygen into the lungs at critical levels.

3. Water Vapor of the Lungs

The considerations above of the physical effects of carbon dioxide in displacing oxygen at altitude are shared equally by water vapor that is constantly being evaporated from the lung surface. Traditionally, the assumption has been made that the gases in the lung are saturated with water vapor at body temperature, but on reflection it will be seen that the physics of this system cannot justify such a conclusion without modification, particularly at high rates of ventilation. The energy expended in evaporating water from the alveolar surface must produce a cyclic variation in temperature of the blood leaving the lung capillaries. It is also known that the saturation of the gases depends on the diffusion of water vapor throughout the space, and thus the ratio of surface to volume will influence the degree of saturation attained at any time. The facts of the case are better stated as saturation at the temperature of the alveolar, bronchial, and tracheal gases, with respect to the time of exposure to the evaporating surface. Experimentally it has been known that the degree of saturation of the whole breath is considerably less than calculated on the assumption of saturation at body temperature,[89, 90] but there is little reason to

[89] G. E. Burch, *Science*, **102**, 619 (1945).

[90] L. H. Marshall: unpublished data from ground level and altitude lung water loss tests, Aviation Medicine Unit, Ind. Hyg. Research Lab., Natl. Inst. of Health, Bethesda, Md.

doubt that at the alveolar surface the saturation is practically that imposed by the local temperature.

4. Critical Altitudes

Practically, the gases in contact with the alveolar surface are diluted by both water vapor and carbon dioxide in the ratio of their combined partial pressures to the total barometric pressure. It is found experimentally that an altitude of about 41,500 ft. is critical for hypoxic symptoms when pure oxygen is being breathed.[79] When pure oxygen is being inhaled, if one assumes a carbon dioxide pressure of 40 mm. Hg and a water vapor pressure of 47 mm. Hg the pressure of oxygen at 41,500 ft. can be no greater than 45 mm. Hg, equivalent to a hemoglobin saturation of not more than 80 per cent. This condition is attained when breathing ambient air at a level not strictly definable unless assumptions concerning the ventilation rate and respiratory quotient are made, but it is usually found that the critical level for unacclimatized individuals is at about 15,000 to 16,000 ft.[79]

The altitudes at which perceptible impairment, that is, objectively demonstrable impairment, is effected under the two conditions given above vary with the tests used to demonstrate it. Thus, effects on night vision are found at very low levels and necessitate the use of oxygen from the ground up for night flying even though low-level flying is to be carried out.[79] This finding from military experience should be one of the first to be applied to civilian flight, especially in passenger transport where hazard to the pilot is carried over directly to large numbers of individuals. At 10,000 to 12,000 ft. the ability to adapt the eyes to night vision and the ability of discrimination of objects is cut to about one half when breathing ambient air.[79] The addition of enough oxygen to raise the partial pressure to that at ground level will correct this deficiency. In general, the use of oxygen is to be recommended at 10,000 ft. if operations are carried on for several hours. The exact time of onset of deficiency for different individuals varies a great deal and prophylaxis is based on the most conservative interval for safety: a 6-hour margin at 10,000 to 12,000 ft., 2-hour at 12,000 to 15,000 ft., and none above 15,000 ft. have been found to be compatible with reasonable safety in selected groups of men, as in the military services,[79] but more recently the use of oxygen on all flights above 10,000 ft. has been ordered.[78] Considerable caution should be exercised in transferring these values to civilian flying, especially to pilots of private craft.

5. Decompression Sickness

In discussing the effects of ascent it was indicated that the onset of effects from inert gas due to the supersaturation caused by ascent to altitude was usually delayed. This necessitates the discussion of these effects as they appear during sustained low pressure. The similarity of this condition to that found after decompressing to one atmosphere from high pressures is great enough to enable the same general approach to be carried over directly.

Because the terminology of these effects has been rather uncritical in its origin from compressed-air experience, workers in low-pressure studies have developed

more specific interpretations of the names for the phenomena which occur: thus, the development of intravascular bubbles is called "aeroembolism" while extravascular bubbles are relegated to the category of "bends," which comprises both phenomena in compressed-air terminology except for bubbles in the lungs, which in both cases is called "chokes." Reference is made to these terms only because they appear in the literature of both fields and often constitute the only detail of symptomatology. In view of the fact that the theory that gas bubbles are the cause of the pain and other sequelae to decompression is contested with some reason by investigators[79, 91, 92] the term "aeroembolism" has also been subject to some criticism. It is admitted, however, that in the fulminating cases of decompression sickness bubbles are found both intra- and extravascularly and they certainly play a large part in the derangement of the body mechanisms whether primary or secondary in point of time.[91, 93–96] The fact that recompression brings immediate relief lends great weight to the bubble theory of decompression sickness, whether of extra- or intravascular character.[79]

The appearance of bubbles in the vascular system has been shown to occur in animals at 45,000 ft. with great regularity even in the presence of oxygen breathing throughout the ascent.[95] These observations indicate that the removal of inert gases from the body is not fast enough to prevent the formation of persistent free-gas phases and that once these bubbles are formed they continue to grow until they can be demonstrated as circulating or embolic entities and within the tissues. Attempts to demonstrate bubbles within cells, particularly those not containing fat inclusions, have been largely unsuccessful[91, 96] and even extravascular bubbles have not been observed in experimental animals after death at 45,000 ft.[95] despite the fact that rather large gas accumulations between muscle masses, under the skin, and near the joints have been demonstrated in human subjects.[91] Another disconcerting fact concerning the etiology of symptoms from decompression sickness is that bends pain can be reduced by the occlusion of arterial vessels leading to the region affected.[79] This is not compatible with the embolic theory or local ischemia unless the action involves the compression of vascular or other sensory nerves that are stimulated by the local effects of emboli within the vessels. The fact that as little as 50 mm. Hg pressure over the tissues proximal to the site of bends pain will relieve the symptom indicates that the precise mechanism is not yet explainable by the mechanisms carried over from compressed-air studies.[79]

The time of onset of symptoms of decompression sickness is inversely related to the rate of ascent, as described previously,[93] and is further related to the product

[91] E. N. Harvey, *Bull. New York Acad. Med.*, **21**, 505 (1945).

[92] J. W. Bean, *Physiol. Revs.*, **25**, 1 (1945).

[93] H. R. Catchpole and I. Gersh, *Naval Med. Research Inst., Research Project X-284, Rept.* No. VI (1945). Also in *J. Cellular Comp. Physiol.*, **27**, 15 (1946).

[94] H. R. Catchpole and I. Gersh, *Naval Med. Research Inst., Research Project X-284, Rept.* No. VII (1945). Also in *J. Cellular Comp. Physiol.*, **27**, 27 (1946).

[95] I. Gersh and H. R. Catchpole, *Naval Med. Research Inst., Research Project X-284, Rept.* No. VIII (1945).

[96] D. M. Whitaker, L. R. Blinks, W. E. Berg, V. C. Twitty, and M. Harris, *J. Gen. Physiol.*, **28**, 213 (1945).

of altitude and duration of exposure at each altitude.[79] Thus, unless the precaution of thorough denitrogenation is taken before ascent, there is always the possibility of the formation of bubbles provided the altitude is great and the stay protracted. In view of these considerations it seems desirable to assume that bubble nuclei are always present or at least are being continuously formed in the various tissues of the body, and that their chances of survival and growth are enhanced in proportion to the concentration of inert gases. The site of such activity may well be the loci at which the respiratory gases are handled normally by each tissue, thus accounting for the low incidence of patent bubbles in tissue cells, where gas exchange is diffuse, as compared with the high incidence in the blood, where the intensity of gas exchange is of a very high order.

Harvey's theory[91] that hydrostatic factors are basically responsible for the initiation of bubble nuclei is based on the observations that exercise and straining are accelerating factors in bubble formation and that the accompanying rise in carbon dioxide concentration is less effective. Because this subject is being investigated actively at the present time, and because a good deal of the work done during the last several years under security classification has not yet been published, a thorough-going analysis cannot be made. It is a well-documented fact, however, that performance of muscular exercise is a predisposing factor for bends and is thus a variable in the determination of the time of onset of decompression sickness symptoms.[79, 91, 94, 96]

The effect of temperature on the production of symptoms of decompression sickness has not been conclusively demonstrated at altitude,[79] but the fact that a predisposition to such symptoms in caisson workers subject to chilling can be shown[97] leads to the assumption of a conservative point of view. The maintenance of comfortable skin temperatures by electrical heating for the preservation of the highest degree of co-ordination in the performance of flight duties obviates, except in the case of accident, the need for consideration of the effects of cold on decompression sickness. The rationale of the effect of cold at altitude is based on the vasoconstricting action of cold in the skin, inducing an interference with the elimination of inert gases, and the production of shivering, which tends to exaggerate the effects of muscular tension over those normally found.

There are at least two other variables that have been found to correlate directly with the incidence of decompression sickness: age and linear density, i.e., pounds per unit height.[98] Similar relations have been determined for decompression from high-pressure atmospheres.[99, 100] The manner in which age increases the incidence of symptoms is not clear except perhaps in that the circulatory resiliency of young individuals may minimize effects that would be reported as noticeable in older men.

[97] H. Gerbis and R. Koenig, *Drucklufterkrankungen*. Thieme, Leipzig, 1939.

[98] Aero Medical Laboratory Staff, *AAF Manual No.* 25-2 (March, 1945).

[99] A. R. Behnke, *Bull. New York Acad. Med.*, **18**, 561 (1942).

[100] I. Gersh, G. E. Hawkinson, E. N. Rathbun, and A. R. Behnke, *Naval Med. Research Inst., Research Project X-284, Repl.* No. **II** (1944). Also in *J. Cellular Comp. Physiol.*, **24** 35 (1944).

It would be more understandable if the differential were only in the severity of symptoms because the effects on the capillary vessels of older men would be expected to be more drastic. The factor of linear density is undoubtedly tied up with body fat and the accompanying difference in vascularization of the tissue. As shown by Gersh,[95] the fatty tissues are poorly ventilated because the effective ratio of capillary surface to tissue volume is low as compared with tissues such as muscle, which are known to be free of extravascular bubbles.

6. Acclimatization

The repeated or continuous exposure of individuals to high altitudes has been studied mainly in connection with mountaineering and in connection with a few industries such as the Andean sulfur mining in Chile.[101] The effects noted were exclusively concerned with the reduction of the partial pressure of oxygen since under the prevailing altitude levels decompression effects would not appear. The adjustments accomplished by the body under prolonged hypoxia of mild degree are mainly in an increase in the number of red cells and their hemoglobin content, and in the tidal volume and rate of ventilation of the lungs, as well as changes in the circulatory efficiency: all directed to the more adequate transport of oxygen to the tissues.[98, 102] Ruff and Strughold laid great emphasis on these reactions and recommended the regular exposure of aviators to these conditions at mountain rest camps.[103] It is apparent, however, that the use of supplementary oxygen at the great heights attained by present aircraft largely does away with the desirability of such acclimatization. It would be of value at intermediate levels only for protracted sojourn, such as described above. These changes take place with the passage of time in normal individuals though not without the symptoms and temporary disabilities collectively known as mountain sickness, i.e., cyclic breathing, nausea, syncope, etc.

C. CHARGING OF THE BODY WITH GAS IN DESCENT: RECOMPRESSION

1. Re-solution of Gases. Relief of Decompression Sickness

One of the most comforting aspects of exposure to decreased barometric pressure is the fact that most of the dangers involved in this condition can be readily eliminated by recompression to atmospheric pressure. The exceptions are cases where a shock-like condition has developed to the point of collapse or just short of it, and where the simple restitution of high partial pressure of oxygen will not correct the trauma to the peripheral vascular bed and the attendant hemoconcentration. Bends pain, chokes, and even serious central effects will respond rapidly to recompression if recompression is instituted early enough. The remission of symptoms usually occurs at intermediate altitudes and nearly always before reaching ground level. This procedure is not a cure until some time has elapsed, since reascent within a reasonably short time will bring almost immediate recurrence of symptoms at the

[101] D. B. Dill, *Life, Heat, and Altitude.* Harvard Univ. Press, Cambridge, Mass., 1938.
[102] W. R. Boothby, *Proc. Staff Meetings Mayo Clinic*, **20**, 209 (1945).
[103] S. Ruff and H. Strughold, *Grundrisse der Flugfarhtmedizin.* Barth, Leipzig, 1939.

same site.[98] The reason for this delay in recovery is the same as in diving and caisson recompression: that is, the re-solution of bubbles is slowed down in direct proportion to their loss of surface by compression.[104] For all practical purposes, recompression and not resaturation is the important factor in relief from decompression sickness per se, but elimination of the hypoxic effects depends upon resaturation of the blood with oxygen, which is of course rapidly effected.

2. *Mechanical Effects of Recompression*

The mechanical effects of recompression are as hazardous as under similar conditions in work at positive pressures. The patency of the eustachean openings and those of the several sinuses must be assured in order to prevent the injection of blood into the capillary bed of the mucosa lining the various cavities in question. As stated earlier,[105] the pressure necessary to rupture the capillary walls is quickly attained in descent, and damage ranging from petechial to massive hemorrhage has been observed regularly in individuals who have difficulty in clearing these passages.[98, 103]

During descent from altitudes at which oxygen must be used there is incurred a condition that is called "delayed acute aero-otitis media." It results from the charging of the middle ear with a high percentage of oxygen that is subsequently lost by absorption into the blood. If the nitrogen influx is not maintained at a proper rate, and it seems usually not to be unless the eustachean passage is intermittently opened, then a negative pressure develops in the middle ear, sealing the eustachean opening and eventually causing a varying degree of pain and discomfort, especially in individuals who are asleep. Practical prophylaxis has been shown by Bowen[106] to consist in removing the oxygen mask at air-breathing levels during descent, and prior to this, if feasible, ventilating the ear and sinuses with air during a "stage" descent, while interspersing oxygen breathing during halts at each stage. When difficulties of this nature arise in indoctrination and altitude-chamber work a more radical procedure can be applied. In this instance descent is made with air from even the highest levels since the time for descent can be made so short that supplementary oxygen need not be used. The ability to open the eustachean tubes must be assured before such maneuvers are attempted, yet it is surprising that with such rapid descent individuals having some difficulty at ordinary rates of descent will find less difficulty, presumably due to the continuous flow of gas into the ear.

3. *Rate of Recompression*

The rate of descent that can be effected is limited mainly by the several unquantitative variables and idiosyncrasies of sinus and ear ventilation, as suggested above and as described for divers and caisson workers. Recompression from 30,000

[104] J. B. H. Kuper, *Rept., Aviation Medicine Unit, Ind. Hyg. Research Lab., Natl. Inst. Health,* Bethesda, Md. (1942).

[105] C. L. Evans, *Starling's Principles of Human Physiology.* 8th ed., Lea and Febiger, Philadelphia, 1941.

ft. and above has been effected in the space of a minute routinely in the course of experimental work[106] without any untoward effect. With these rates of descent the compressional inflow effects described by Bean[92] should be apparent subjectively as well as objectively, yet no mention is made in the literature of such effects on descent from high altitudes. In a preliminary trial, continuous gas analysis of respired air indicated temporary carbon dioxide retention during rapid descent with a corresponding excess for several minutes following descent. The respiratory rate also showed an increment in the period immediately following the descent.[107] The data from experiments and experience with free fall in parachuting[98] indicate that mechanical effects are the only restricting factors in rapid descent. It is, of course, necessary to take into account the absolute pressure as well as the rate of descent because of the interval in which respirable air must be available. This is a real difficulty in parachuting from great heights because even in free fall the rate of descent is slow enough so that hypoxia may develop when an individual is jumping from 40,000 ft. About 2½ minutes elapse in free fall from this altitude, and an open chute descent would take 24½ minutes. Free fall is the method of choice until at least half an atmosphere of pressure is attained, not only from the point of view of avoiding hypoxia but also because of the excessively low temperatures at these heights.[98]

D. COMPARISON OF EFFECTS OF HIGH AND LOW ATMOSPHERIC PRESSURE

In the introduction to this chapter it was pointed out that the effects of barometric changes differed qualitatively as well as quantitatively in the ranges of absolute pressure above and below standard atmospheric pressure. The similarities and differences have been noted in the several sections. In the following lines a brief statement is made of the similarities and differences of effects on the physiology of normal individuals. The clinical and pathological features must be largely inferred from their physiological basis, and further detail should be sought in the several competent reviews, both classical and current, that are cited in the list of references.

The mechanical effect of pressure change on the ear and sinuses is qualitatively similar for both low-pressure and high-pressure atmospheres. The principal effect occurs on increase of pressure when for some reason pressure equalization by passage of air into the lumens cannot be effected. The main result is displacement of blood from the body into the capillary system of the tissues lining these cavities, with hemorrhage into the lumen. In the case of the middle ear, bursting of the drum also may result. A fall in pressure is usually not attended by severe effects but may result in driving blood out of the tissues within the cavity and forcing the ear drum outward. The construction of the normal passages connecting these structures with the exterior is mechanically adapted to relieve internal pressure readily.

[106] W. J. Bowen, *U. S. Naval Med. Bull.*, **44**, 247 (1944).

[107] Unpublished current work by the Aviation Medicine Unit, Ind. Hyg. Research Lab., Natl. Inst. Health, Bethesda, Md.

The mechanical effects of atmospheric pressure change on gases enclosed within soft-walled structures such as the gastrointestinal tract are quantitatively different in the two ranges of pressure in that the partial pressure of water enhances the volume change on decrease in pressure in inverse proportion to the absolute pressure. On increase of pressure there is no deleterious effect.

The effects of the partial pressure of oxygen with change in atmospheric pressure are qualitatively different in the two ranges of abnormal pressure. At increased pressures there is a tendency for "oxygen poisoning" to increase in proportion to the absolute pressure above a relatively low limiting value. At decreased atmospheric pressure there is conversely a progressive asphyxiation due to interference with the oxygen transport to the tissues and finally with the pressure-labile oxidative processes in the tissues.

The effects of the partial-pressure changes of inert gases are qualitatively similar in the two ranges of atmospheric pressure, in that reduction of pressure leads to supersaturation of the dissolved gases, with the consequent danger of the formation of bubbles within and without the vascular system. The causal relation between bubbles and the symptoms of decompression sickness is not wholly established but the immediate relief of symptoms by recompression indicates a real relationship.

At high atmospheric pressures there is observed an additional effect on the central nervous system that has been attributed to the inert gases. A causal relation of carbon dioxide to it has been suggested in view of the lack of chemical activity of the inert gases, but neither approach can fully account for the observed effects. At low atmospheric pressures the biologically active gases produce such marked effects that no observations on the part played by inert gases, except as passive diluters of the oxygen, have been made.

At present, there are two bibliographies of the literature in this field.[108, 109] Because of developments of the aviation aspects during World War II, reviews of a critical nature now are beginning to appear. Declassification of much of the experimental work from restricted categories has progressed slowly and to date much of it has not yet been published in the professional journals. It is hoped that the references given here to reports of restricted circulation will aid the reader as an indication of the existence of the work and a subsequent search of the abstracting journals may reveal the ultimate place of publication.

[108] E. C. Hoff and J. F. Fulton, *A Bibliography of Aviation Medicine.* Thomas, Springfield, Ill., 1942, p. 237.

[109] E. C. Hoff, *A Bibliographical Source-Book of Submarine and Compressed Air Medicine.* U. S. Government Printing Office, Washington, D. C., 1947.

CHAPTER SEVEN

The Mode of Entry and Action of Toxic Materials

FRANK A. PATTY

In order to plan the prevention of injury from toxic materials in industry it is essential that we have a clear understanding of how these materials enter the body, how they act therein, and how they are eliminated. In order better to understand these processes, we should understand respiration and circulation and their role in absorption and elimination. This in turn necessitates an understanding of the gas laws, with an ability to apply them to the solution of gases in liquids and specifically, the body fluids. We need also to know how different materials act upon the body and to understand the different types and degrees of physiological response.

I. Classification of Contaminants

The earth is surrounded by a gaseous atmosphere of rather fixed composition: 78.09 per cent nitrogen, 20.95 per cent oxygen, 0.93 per cent argon, 0.03 per cent carbon dioxide, insignificant amounts of neon, helium, and krypton, and traces of hydrogen, xenon, radioactive emanations, oxides of nitrogen, and ozone, with which may be mixed anywhere up to 5.0 per cent water vapor. Any of these gases in greater proportion than usual, or any other substance present in the atmosphere, may be regarded as a contaminant, or as atmospheric pollution. The possibilities of contamination are legion, but we may classify them according to their physical state, their chemical composition, or their physiological action.

A. PHYSICAL CLASSIFICATIONS

1. Gases and Vapors

While, strictly speaking, a gas is defined as a substance above its critical temperature and, similarly, a vapor, the gaseous phase of a substance below its critical temperature, the term "gas" is usually applied to any material that is in the gaseous state at 25° C. and 760 mm. Hg pressure; and "vapor," to the gaseous phase of a substance ordinarily liquid or solid at 25° C. and 760 mm. Hg pressure. The usage

distinction between gas and vapor is not sharp, however; for example, hydrogen cyanide, which boils at 26° C., is always referred to as a gas, while hydrogen chloride, which boils at −83.7° C. is sometimes referred to as an acid vapor.

2. Particulate Matter—Dispersoids

This classification includes both liquid and solid particles ranging from 100 μ in diameter (1/254 in.) down to little more than molecular size.

(*a*) Solid — dust. When solid particles have been dispersed by disintegration they are called dusts.

(*b*) Liquid — mists. Mists are made up of liquid particles that have been dispersed, as by atomization.

3. Particulate Matter—Condensoids

(*a*) Solid — fumes. Condensates of solid particles that have condensed in the atmosphere are called fumes.

(*b*) Liquid — fogs. Fogs consist of liquid particles of condensates.

4. Other Physical Classifications and Definitions

Instead of the above very useful method of classifying materials for industrial hygiene control purposes, they may be regrouped into the classic division of gases, liquids, and solids.

Aerosols. A dispersion or any suspension of fine solid or liquid particles in the air, or other gaseous medium, is called an aerosol.

Smoke. The term "smoke" is usually used to refer to gaseous products of combustion, when rendered visible by the presence of particulate carbon, but is used also to designate mixtures of various types of contaminants arising from incomplete combustion, or in isolated instances is used to describe a cloud resembling such products of combustion.

B. CHEMICAL CLASSIFICATIONS

Chemical classifications are variously based upon the chemical composition of the air contaminants, and may vary widely depending upon the aspect of the composition to be emphasized. The classification used in Volume II of this book is one example of chemical classification.

C. PHYSIOLOGICAL CLASSIFICATIONS

As has been pointed out by Henderson and Haggard,[1] the physiological classification of air contaminants is not entirely satisfactory because, with many gases and vapors, the type of physiological action depends upon concentration. For instance a vapor at one concentration may exert its principal action as an anesthetic, while a lower concentration of the same vapor may, with no anesthetic effect, injure the nervous system, the hematopoietic system, or some visceral organ. Although it

[1] Y. Henderson and H. W. Haggard, *Noxious Gases.* 2nd ed., Reinhold, New York, 1943.

is frequently impossible to place a material in a single class correctly, a suggested physiological classification follows.

1. Irritants

Irritant materials are corrosive or vesicant in their action. They inflame moist or mucous surfaces. They have essentially the same effect upon animals as upon men, and the concentration factor is of far greater significance than the time, duration of exposure, factor. Some representative irritants are:

(*a*) Irritants affecting chiefly the upper respiratory tract: aldehydes (acetaldehyde, acrolein, formaldehyde, paraform), alkaline dusts and mists, ammonia, chromic acid, ethylene oxide, hydrogen chloride, hydrogen fluoride, sulfur dioxide, sulfur trioxide.

(*b*) Irritants affecting both the upper respiratory tract and lung tissues: bromine, chlorine, chlorine oxides, cyanogen bromide, cyanogen chloride, dimethyl sulfate, diethyl sulfate, fluorine, iodine, ozone, sulfur chlorides, phosphorus trichloride, and phosphorus pentachloride.

(*c*) Irritants affecting primarily the terminal respiratory passages and air sacs: arsenic trichloride, nitrogen dioxide and nitrogen tetroxide, and phosgene. (To the extent that their action frequently terminates in asphyxial death, lung irritants are related to the chemical asphyxiants.)

2. Asphyxiants

The asphyxiants exert their effects by interfering with the oxidation of the tissues. Their action is well understood and, in general, the response of human beings is similar to that of many animals, including dogs. This group can be subdivided into simple and chemical asphyxiants. Simple asphyxiants are physiologically inert gases that act principally by dilution of the atmospheric oxygen below the partial pressure required to maintain an oxygen saturation of the blood sufficient for normal tissue respiration. The chemical asphyxiants, on the other hand, through chemical action either prevent the blood from transporting oxygen from the lungs or else prevent normal oxygenation of the tissues, even though the blood is well oxygenated. Examples of asphyxiants are:

(*a*) Simple asphyxiants: carbon dioxide, ethane, helium, hydrogen, methane, nitrogen, nitrous oxide.

(*b*) Chemical asphyxiants: carbon monoxide, which combines with hemoglobin; cyanogen, hydrogen cyanide, and nitriles, which inhibit tissue oxidation by combining with cellular catalysts; aniline, methyl aniline, dimethyl aniline, and toluidine, which form methemoglobin; nitrobenzene, which has the nitrite effect, forms methemoglobin, lowers blood pressure, disturbs and finally halts breathing; and hydrogen sulfide, which causes respiratory paralysis. (See also lung irritants.)

3. Anesthetics and Narcotics

This group exerts its principal action as simple anesthesia without serious systemic effects, and the members have a depressant action on the central nervous

system governed by their partial pressure in the blood supply to the brain. The following examples are arranged in the order of their decreasing anesthetic action compared with other actions: (*a*) acetylene hydrocarbons (acetylene, allylene, crotonylene); (*b*) olefin hydrocarbons (ethylene to heptylene); (*c*) ethyl ether and isopropyl ether; (*d*) paraffin hydrocarbons (propane to decane); (*e*) aliphatic ketones (acetone to octanone); (*f*) aliphatic alcohols (ethyl, propyl, butyl, and amyl); (*g*) esters (not particularly anesthetic, but placed here for want of a better classification)—they hydrolyze in the body to organic acids and alcohols.

4. Systemic Poisons

(*a*) Materials that cause organic injury to one or more of the visceral organs: the majority of the halogenated hydrocarbons

(*b*) Materials damaging the hematopoietic system: benzene, phenols, and to some degree toluene, xylene, and naphthalene

(*c*) Nerve poisons: carbon disulfide, methyl alcohol, thiophene

(*d*) Toxic metals: lead, mercury, cadmium, antimony, manganese, etc.

(*e*) Toxic nonmetal inorganics: compounds of arsenic, phosphorus, selenium, and sulfur; fluorides

5. Particulate Matter Other Than Systemic Poisons

(*a*) Fibrosis producing dusts: silica, asbestos

(*b*) Inert dusts: carborundum, carbon, emery

(*c*) Dusts causing allergic reactions: pollen, wood, resins, and many other organic dusts

(*d*) Irritants: acids, alkalies, fluorides, chromates

(*e*) Bacteria and fungi

II. Respiration

A. MECHANICS OF RESPIRATION

During inspiration, air forced by atmospheric pressure enters the nasal openings, passes through the pharnyx, larnyx, trachea, bronchi and bronchioles, through the terminal bronchioles, the respiratory bronchioles and alveolar ducts, into the air sacs or alveoli, filling the void created by involuntary muscular expansion of the thoracic cavity. Expiration may be either by muscular effort or by elastic contraction of lung tissue, but in quiet breathing contraction is thought to be entirely passive. The normal function of respiration is to supply atmospheric oxygen through the alveolar walls to the blood for distribution to the tissues, and to remove carbon dioxide resulting from oxidation within the cells. The oxygen and carbon dioxide exchange in the tissues is sometimes referred to as tissue or internal respiration, as distinguished from the aeration of the lungs or external respiration.

B. LUNG STRUCTURE, VITAL CAPACITY, AND THE DEAD SPACE

The tracheobronchial tree as described by Miller[2] is supported by cartilage, the trachea being a series of open cartilaginous rings or crescents connected on the posterior side by bundles of muscle. The rings are joined to each other by a dense layer of connective tissue. The result is a rather rigid ribbed tube capable of some adjustment in diameter. This tube divides into the right and left main bronchi extending downward at approximately 20 degrees for the right, and 40 degrees for the left branch. The bronchi are further divided and subdivided into smaller and smaller bronchial passages. There is a muscular network essentially transverse to these passages, and as the passages decrease in diameter the cartilaginous rings become less complete, finally losing their crescent shape to become merely small plates of cartilage. As the cartilage decreases there is an increase in the proportion of muscular tissue. Cartilaginous support finally disappears toward the outer end of the bronchioles, where the diameter is about 0.5 mm. These terminal bronchioles connect with respiratory bronchioles which branch into alveolar ducts, terminating in the alveoli. These bronchioles range from 1.5 to 0.2 mm. in length and are about 0.2 to 0.4 mm. in diameter.

Normally the lungs fill about 80 per cent of the total chest cavity. An average man can inhale about 3½ liters of air by forced effort after an ordinary exhalation. Likewise, he can forcibly exhale about 1 liter after an ordinary exhalation. The sum of these, about 4½ liters, is called the vital capacity. There is in addition about 1 to 1½ liters residual air which cannot be expelled by forced exhalation but remains in the lungs to aerate the blood during exhalation. Thus there is a total volume in excess of 5½ liters, of which less than 10 per cent is used in normal breathing. The approximately 500 ml. of air inhaled and exhaled during normal respiration is called tidal air, and of this 500 ml. about 150 ml. is required to fill the tracheobronchial tree or anatomical dead space—that portion of the respiratory tract consisting of thick-walled passages through which no interchange of gases between blood and air can occur. During an ordinary 500 ml. inspiration then, 150 ml. practically unaltered atmospheric air fills the dead space, while 350 ml. enters the alveoli and respiratory exchange area of the lungs. Then during expiration, alveolar air containing 5 to 6 per cent carbon dioxide, and 12 to 14 per cent oxygen, is forced from the alveoli through the dead space, leaving this dead space filled with alveolar air. The first part of the exhalation is essentially atmospheric air and the last part alveolar air, with the mixture growing richer in alveolar air throughout expiration. Undiluted alveolar air can be obtained successfully only from air forcibly exhaled at the end of an ordinary respiration. Failure to consider this well-established fact can lead to serious errors in sampling expired air, as for instance in the determination of the radon content of the alveolar air. The maximum rate of physical activity that can be maintained by an individual is probably more dependent upon his maximum breathing capacity, minute ventilation, than upon lung volume. This minute ventilation is

[2] W. S. Miller, *The Lung.* Thomas, Springfield, Ill., 1937.

partially conditioned by frictional resistance along the air passages due to impediments, such as constrictions and abrupt changes in direction, or air passages merging at too great an angle.

C. REGULATION AND CONTROL OF RESPIRATION

The respiratory movements are regulated and controlled chemically as well as by the voluntary and involuntary nervous systems. Carbon dioxide acts as a stimulus to the respiratory center, and the CO_2 tension in the blood is by far the most significant factor of control. It is thought to act by raising the hydrogen-ion concentration of the respiratory center. Lactic acid resulting from strenuous exercise is thought to have a similar effect. Oxygen, or rather lack of it, is likewise a stimulus, but under normal conditions does not come into play because the partial pressure of oxygen in the alveolar air must fall markedly before the oxygen tension of the arterial blood is significantly affected. This is easily understood upon examination of the oxygen dissociation curve for blood, as is illustrated in Figure 1 below. Men with long experience in testing atmospheres in the holds of ships say that they can recognize atmospheres deficient in oxygen by this stimulating effect, but this is not recommended practice even for the well initiated because the margin between irrespirable atmospheres and those causing respiratory distress in the form of hyperpnea and dyspnea is too narrow. The suddenness of the onset of weakness and unconsciousness is so very marked that should a man enter an oxygen-deficient atmosphere by means of a ladder, the probability of his being able to remount the ladder unassisted, after becoming aware of distress, is not favorable.

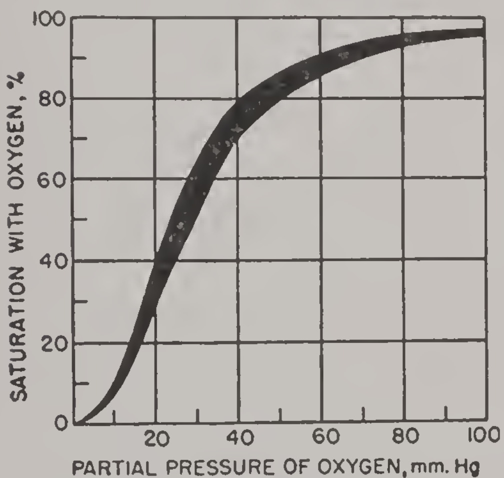


FIG. 1. Dissociation curve of oxyhemoglobin for human blood expressed as the normal range of percentage of saturation with oxygen (*after Barcroft*).

The tension or partial pressure of oxygen in normal air is 20.95 per cent of an atmosphere, which equals 159.2 mm. Hg at sea level. Significant symptoms of distress do not occur until the percentage falls below 16 per cent, while unconsciousness may occur at concentrations below 11 per cent, and breathing soon stops if the oxygen falls below 6 per cent.

D. FUNCTION OF HEMOGLOBIN

The transportation of oxygen from the lungs to the cellular tissues is accomplished largely by means of the hemoglobin in the red cells of the blood. Likewise the carbon dioxide removed from the tissues is transported chiefly by the same agent. Each 100 ml. of arterial blood contains about 15 g. of hemoglobin, which combine with 19 or 20 ml. of oxygen. In blood that is in equilibrium with air at normal atmospheric pressure, about 1 per cent of the total oxygen is in solution in the plasma.

Normal venous blood contains 12 to 14 ml. of oxygen per 100 ml. of blood, and about 1 per cent of this is dissolved in the plasma. For the return trip to the lungs the venous blood carries 55 to 60 volume per cent carbon dioxide and deposits about 10 per cent of this as it takes up its oxygen supply. The amount of carbon dioxide in simple solution is about 3 volume per cent in the venous blood and 2.5 volume per cent in the arterial blood. Since the blood in making its circuit flows through the capillaries of the lungs in approximately 1 second,[3] and through active tissue in a similar time, it is evident that mere solution of oxygen and carbon dioxide cannot account for the exchange of these gases, even though the equilibration in the lungs is highly efficient. The speed of exchange is due to the light combination of these gases with hemoglobin to form oxyhemoglobin and carbhemoglobin, respectively, as well as to the presence of catalysts in the red cells that play an important part in the oxygen and carbon dioxide exchange. Carbonic anhydrase is said by Best[3] enormously to increase in either direction the reversible chemical reaction $H_2CO_3 = CO_2 + H_2O$, while oxidation and reduction in the tissues are greatly accelerated by oxygen-activating catalysts or by dehydrogenases.

E. CIRCULATION AS A FACTOR, AND ITS REGULATION

Since the oxygen in the lungs cannot take part in the metabolic process until it has entered the blood stream and then been transported to the tissues, it is evident that the circulation rate is an important factor in respiration. The blood volume is usually slightly greater than the lung capacity. For a normal man it is approximately 6 to 7 liters.[3]

The time required for a complete circuit of the blood varies with exercise, the part of the body supplied, and many other factors, but averages somewhat less than 1 minute. The normal heart stroke is about 60 to 70 ml., with a resting pulse of 68 to 72 per minute, giving a minute volume of 4 to 5 liters. Exercise can increase the heart stroke to 100 or 200 ml. and the pulse rate to 170 or 180. Environmental temperatures above 30° C. increase the minute volume 5 to 30 per cent. Digestion of food increases the basal minute volume by 30 to 40 per cent for about 3 hours. Emotional strain causes an increase of 15 to 25 per cent. pH changes have an effect, as do naturally occurring, as well as foreign, chemicals having a vasoconstrictor or vasodilator reaction. Also, just as the amount and content of the venous supply to the lungs play a major role in regulating the breathing required to keep the arterial blood constant, so does the circulation depend on breathing, and any retardation of breathing will be quickly followed by a change in circulation. Henderson[4,5] strikingly demonstrated the control of circulation by breathing when he showed that excessive pulmonary ventilation could induce failure of the circulation. The part played by respiration in the action of atmospheric contaminants upon the body will be discussed later.

[3] C. H. Best and N. B. Taylor, *The Physiological Basis of Medical Practice.* 3rd ed., Williams & Wilkins, Baltimore, 1943.

[4] Y. Henderson, *Am. J. Physiol.*, **25**, 310 (1910).

[5] Y. Henderson and H. W. Haggard, *J. Biol. Chem.*, **33**, 355 (1918).

III. Absorption, Distribution, and Elimination

A. MODES OF EXPRESSING CONCENTRATIONS

The extent of atmospheric contamination in the gaseous phase is frequently expressed as parts per million (p.p.m.), denoting units of volume in 1,000,000 volumes, and is usually corrected to 25° C. and 760 mm. Hg pressure. This is a convenient mode of expression and, for routine examinations of workroom atmospheres, the actual conditions are frequently not sufficiently removed from this standard to require temperature–pressure corrections. Since comparisons in p.p.m. are on a volume—hence molecular—basis they have no direct relation to the weight–volume expression of milligrams per liter occasionally used, especially in foreign technical publications. The milligrams per liter unit has the advantage of being more readily compared with existing pharmacological and dosage data, expressed as milligrams per kilogram of body weight. On the whole, however, the p.p.m. unit has proved much more convenient and expressive in industrial hygiene, where low concentrations of contaminants are the rule. Variations in the expression of parts by volume are: per cent by volume, parts per thousand, and parts per ten thousand. Per cent by volume is usually used when the concentrations are on the order of 0.1 per cent (1000 p.p.m.) or greater. Parts per thousand or per ten thousand are little used expressions, apt to be confusing, which are happily falling into disuse. One per cent by volume = 10,000 parts per million (p.p.m.) = 10 parts per thousand = 100 parts per ten thousand = a partial pressure of 7.6 mm. Hg at sea level. One gram mole of a perfect gas or vapor has a volume of 24.45 liters at 25° C. and a pressure of 760 mm. Hg. Therefore under these conditions:

$$1 \text{ p.p.m.} = \frac{\text{molecular weight}}{1000 \times 24.45} \text{ mg. per liter;}$$

$$\text{and } 1 \text{ mg. per liter} = \frac{24.45 \times 1000}{\text{molecular weight}} \text{ p.p.m.}$$

A conversion table for gases (p.p.m. to mg. per liter and mg. per liter to p.p.m.) is given in this volume. Another method of expressing gas concentrations is the partial pressure method, using the unit of the pressure exerted by one millimeter of mercury. This is convertible directly to per cent by volume by multiplying by 100 and dividing by the barometric pressure; or to p.p.m. by multiplying by 1,000,000 and dividing by the barometric pressure:

$$\frac{\text{partial pressure of one constituent}}{\text{total barometric pressure}} \times 1{,}000{,}000 = \text{p.p.m. of constituent}$$

When the contaminant is dispersed in the atmosphere in solid or liquid form, as a mist, dust, or fume, its concentration must be expressed either on a weight per volume basis or particles per volume basis. Liquids and toxic solids are usually expressed as milligrams per cubic meter, or per 10 cu. m. to approximate the maximum amount inhaled in one 8-hour day by a workman doing moderately heavy work. This standard was originally based on 20 liters per minute × 60 minutes × 8 hours = 9600 liters = 9.6 cu. m. Henderson and Haggard[6] estimate the average

[6] Y. Henderson and H. W. Haggard, *Noxious Gases*. 2nd ed., Reinhold, New York, 1943.

breathing rate to be 8 liters per minute or about 4 cu. m. per 8-hour day. Since not only the minute volume, but also retention, the physiological dead space, and other factors must be considered in computing daily systemic intake, the validity of the figure, 10 cu. m., is open to question. Those dusts that exert their effects largely within the lungs, rather than throughout the system as a whole, are usually counted microscopically and expressed as million particles per cubic foot of air.

B. VOLUME–PRESSURE–TEMPERATURE RELATIONS

Boyle's law, which states that a perfect gas without change of temperature varies inversely in volume with the pressure to which it is subjected, and Charles' law, which states that at constant pressure the volume of a gas varies directly with the absolute temperature, are usually combined in one operation to convert observed gas or vapor volumes to normal conditions (25° C. and 760 mm. Hg pressure) as follows:

$$\begin{matrix}\text{observed} \\ \text{volume}\end{matrix} \times \frac{298}{\text{obs. abs. temp. (°C.)}} \times \frac{\text{obs. barom. pressure (mm. Hg)}}{760} = \begin{matrix}\text{volume at} \\ \text{normal conditions}\end{matrix}$$

This formula may be used, of course, to convert from any observed temperature and pressure to any desired temperature and pressure by substituting the proper values for the normal condition values as given.

Partial Pressures

Each gas in a mixture exerts a pressure in direct proportion to its per cent by volume. In a sample of dry air, for example, at sea level the percentage composition and partial pressures are:

$$\text{oxygen, } 20.95\% \times 760 \text{ mm.} = 159.22 \text{ mm. p.p.}$$
$$\text{nitrogen (carbon dioxide, and inert gases), } 79.05\% \times 760 \text{ mm.} = 600.78 \text{ mm. p.p.}$$

If, without change in barometric pressure, this air should become humidified to the extent of 50 per cent relative humidity at 25° C., the composition would be altered as follows. Water vapor, 11.88 mm. partial pressure, would appear in the mixture, and since the total pressure does not change, the composition of the atmosphere becomes:

$$\text{water vapor} = 11.88 \text{ mm. p.p.}$$
$$\text{oxygen, } 20.95\% \times (760 - 11.88) \text{ mm.} = 156.73 \text{ mm. p.p.}$$
$$\text{nitrogen, etc., } 79.05\% \times (760 - 11.88) \text{ mm.} = 591.39 \text{ mm. p.p.}$$

Should a sample of this 50 per cent humidified air be transported to a higher altitude and opened for analysis, the partial pressures would decrease but the percentage composition would remain the same. At 750 mm. barometric pressure, for instance, this humidified air would have the partial pressure composition, as follows:

$$\text{water vapor} = \frac{750}{760} \times 11.88 \text{ mm.} = 11.72 \text{ mm. p.p.}$$
$$\text{oxygen, } 20.95\% \times (750 - 11.72) \text{ mm.} = 154.67 \text{ mm. p.p.}$$
$$\text{nitrogen, etc., } 79.05\% \times (750 - 11.72) \text{ mm.} = 583.61 \text{ mm. p.p.}$$

Gases are ordinarily reported on a dry basis but variations in volume due to temperature, pressure, and water vapor changes may be computed by the formula:

$$V_1 = \frac{V_2(P_2 - W_2)(273 + T_1)}{(P_1 - W_1)(273 + T_2)}$$

where V_2 is the observed volume of gas at the observed temperature T_2; V_1 is the calculated volume of gas at temperature T_1; temperatures T_1 and T_2 are in degrees Centigrade; W_2 and W_1 are mm. Hg vapor tension of water at observed and calculated conditions; and P_2 and P_1 mm. Hg are respectively the observed and the calculated barometric pressures. Air and vapors inhaled into the lungs are rapidly saturated with water vapor at body temperature to approach a partial pressure of 47 mm. Hg and, in computing the partial pressure of any vapor in alveolar air, this partial pressure of water must be considered.

C. ROLE OF SOLUBILITY IN ABSORPTION OF GASES AND VAPORS

1. *Solubility Coefficient*

Any gas confined in contact with a liquid dissolves at the surface of the liquid and enters the liquid until its partial pressure in the vapor phase above the liquid is in equilibrium with the gas dissolved in the liquid, that is, the rates of its dissolving and evaporating have become equal. The speed with which equilibrium is reached is a function of the solubility and the relationship of contact surface to volume of liquid—the greater the proportion of surface area, and the lower the solubility, the sooner equilibrium will be reached. At the same time the liquid vaporizes into the space above it until its partial pressure in the atmosphere is in equilibrium with its evaporation pressure in the liquid phase. Henry's law, *the concentration of a gas that will dissolve in a liquid is directly proportional to its concentration in the free space above the liquid*, may be expressed as $C_1/C_2 = K$, where C_1 and C_2 are the molar concentrations of the gas in the liquid and vapor phases respectively, and K is the solubility coefficient. This coefficient is different for each vapor, each liquid, and each temperature.

Henderson and Haggard[7] have proposed that this law be expressed in a more convenient form when applied to the absorption of gases through the lungs into the blood. They suggest $C/C_1 = D$, where D is the coefficient of distribution, C is the concentration in the fluid phase (blood), and C_1 is the concentration in the vapor phase in alveolar air, both concentrations to be expressed on a weight per volume basis (milligrams per liter). This form of the law is particularly convenient for the purpose intended, and it is to be hoped that additional data will be collected to establish the coefficient of distribution of more gases and vapors between the atmosphere and the circulating blood. For a miscible or highly soluble material the coefficient of distribution cannot be approximated by calculation, but for a less readily soluble vapor it can be approximated from its vapor pressure and solubility at body temperature, 37° C. The coefficient of distribution is constant for the same vapor and

[7] Y. Henderson and H. W. Haggard, *Noxious Gases*. 2nd ed., Reinhold, New York, 1943.

liquid at any given temperature regardless of the concentration of vapor in the atmosphere.

The coefficient is known for the solubility of relatively few vapors and gases in blood at body temperature, this being a field that has been insufficiently explored in toxicity studies. It is to be hoped that in the future such studies will include the partial pressure of the vapor, or gas under observation, in alveolar air, and in the body fluids, at time intervals during accumulation and elimination of vapors, as well as at equilibrium. In computing a coefficient of distribution from room-air vapor concentration data, corrections for changes in temperature and partial pressure of water vapor should be made if comparisons are desired with coefficients based upon alveolar air, because alveolar air approaches saturation with water vapor at 37° C. (47 mm. Hg partial pressure). Some of the coefficients that have been established are given in Table 1.

TABLE 1

Distribution Coefficients

Solvent	Coefficient of distribution[a]	Ref. No.
Methyl alcohol	1700	8
Ethyl alcohol	1300	8
Isoamyl alcohol	836	9
Primary n-amyl alcohol	804	9
Secondary isoamyl alcohol	550	9
Acetone	330	10
Methyl n-propyl ketone	167	9
Diethyl ketone	157	9
Methyl isopropyl ketone	101	9
Ethyl ether	15	8
Benzene	6.58[b]	11
Carbon disulfide	5	12

[a] The coefficient of distribution here is the ratio of milligram of solvent per liter of blood to milligram of solvent per liter of alveolar air.

[b] Based upon room air rather than alveolar air.

2. Body Saturation

From the foregoing it is evident that any gas or vapor in the air we breathe tends to pass through the lungs into the blood stream and to be distributed throughout the body. The respiratory tissue in the lungs, which has been estimated to have a surface area of about 55 sq. meters, acts as the exchange surface between blood

[8] Y. Henderson and H. W. Haggard, *Noxious Gases*. 2nd ed., Reinhold, New York, 1943.

[9] H. W. Haggard, D. P. Miller, and L. A. Greenberg, *J. Ind. Hyg. Toxicol.*, **27**, 1 (1945).

[10] A. P. Briggs and P. A. Schaffer, *J. Biol. Chem.*, **48**, 413 (1921).

[11] H. H. Schrenk, W. P. Yant, S. J. Pearce, F. A. Patty, and R. R. Sayers, *J. Ind. Hyg. Toxicol.*, **23**, 20 (1941).

[12] R. W. McKee, C. Kiper, J. H. Fountain, A. M. Riskin, and P. Drinker, *J. Am. Med. Assoc.*, **122**, 217 (1943).

and air. The blood in the capillaries is said to be separated from the air in the alveoli by two membranes of the utmost delicacy, perhaps only one cell in thickness, so it becomes evident that equilibrium between the blood in the lungs and the alveolar air is reached rapidly. The accumulation of the foreign gas or vapor in the body depends upon a number of factors, such as concentration in the air, the solubility of the material in the blood and tissues, the length of exposure, the rate of breathing, the rate of circulation, whether the material is reactive, and other factors.

If a gas is very soluble in the blood, saturation of the body is slow, requiring days, is largely dependent upon the ventilation of the lungs, and is only slightly influenced by changes in circulation: whereas with a very slightly soluble gas such as nitrogen, saturation is very rapid, being nearly complete within a few minutes, is chiefly dependent upon the rate of circulation, and little influenced by the rate of breathing. With gases and vapors that are freely soluble in water and nonreactive, or only slowly reactive, in the body, such as acetone and methanol, the absorption and distribution throughout the body are dependent upon the water content of the tissues. For the fat-soluble vapors, although transport may be chiefly by the aqueous content of the blood, the vapors tend to concentrate in the fatty tissues. With any nonreactive vapors, although the blood and tissue concentrations, short of equilibrium, are proportional to the vapor concentration and functions of the time of exposure, the rate of saturation is, with constant circulation and breathing, a relation peculiar to each vapor and independent of the concentration of the vapor. In other words, the same time is required for the same vapor to reach a given percentage saturation of the body, regardless of the concentration of the vapor in the atmosphere breathed.

It is not practical to speak of the exact time required for complete saturation, as this is a variable, and too indefinite. It is, however, practical to state a time of some percentage saturation such as 50, 60, 70, 80, or even 90 per cent of saturation, but past this point the absorption curve for a gas or vapor of low reactivity becomes rather flat. With a relatively water-insoluble vapor such as benzene, blood saturation occurs so rapidly that even the venous blood may reach 70 to 80 per cent of saturation within 30 minutes, yet relatively complete saturation may require as much as 2 or 3 days. This can be explained by the fact that the fatty tissue, which has the greater affinity for benzene, removes and stores the benzene carried by the blood, but this fatty tissue has in many instances a very meager blood supply and therefore requires a longer period to attain equilibrium.

Of vapors highly soluble in water methanol is typical. About 24 hours inhalation of this vapor is required before the blood is 70 per cent saturated (about 50 times as long as for a similar percentage saturation with benzene), yet relatively complete saturation here requires little longer than with benzene, the difference being that the fatty tissues with their smaller blood supply are not a reservoir for methanol, and distribution throughout the body at equilibrium is directly proportional to the water content of each tissue. Both benzene and methanol are examples of very slightly reactive vapors.

Carbon disulfide, approximately 90 per cent of which has been found to be metabolized, may be cited as an example of a moderately reactive, relatively water insoluble vapor. McKee and associates[12] have reported upon the blood saturation with carbon disulfide in inhalation exposures of dogs. The absorption curve for carbon disulfide would be expected, from its physical and chemical properties, to resemble that for benzene except as it may be affected by a higher rate of metabolism, and McKee's data indicate that this is the case. If the points on his graph for the blood saturation of a dog breathing 50 p.p.m. carbon disulfide are connected by an exponential curve, the data indicate a saturation of around 90 per cent at the end of a 3½-hour exposure. The coefficient of distribution of CS_2 between blood and room air at this percentage saturation was 4.3 on a milligrams per liter basis.[13] If this were corrected for alveolar air temperature and humidity the value at equilibrium would be approximately 5. Desaturation was rapid and, for single exposures, more or less complete within 2 to 6 hours. This is similar to the desaturation curve for benzene. During accumulation or absorption the arterial blood is saturated to a higher degree than venous blood, while at equilibrium or saturation the concentration is the same in each, and during elimination the concentration of benzene in the arterial blood is lower.

The difference in vapor concentration between arterial and venous blood is dependent upon the solubility or coefficient of distribution of the particular vapor. With a very soluble vapor the difference is negligible, while with a slightly soluble vapor, such as benzene, the difference is marked, and during accumulation the arterial blood, once the lungs are filled with vapor by the first few inhalations, is equilibrated with air only slightly less in concentration of vapor than the air inhaled. In other words, the blood passing through the lungs is not sufficient to absorb an appreciable percentage of the vapor from the alveolar air. This has an important bearing on brief exposures to high concentrations of slightly soluble vapors. The arterial blood supply to the brain is large: therefore, brief exposures to high concentrations of anesthetic gases or vapors of low solubility produce rapid effects even though the degree of saturation of the body is very low. The administration of ether is a good example of this point. Moderate concentrations may be given that will induce unconsciousness after ½ hour or more and the effects will be somewhat prolonged, or concentrations may be given sufficiently high to induce unconsciousness quickly and have recovery occur shortly after removal from exposure, providing the exposure has not been prolonged. This also has a practical bearing in degreasing work where a short exposure to high concentrations of trichloroethylene, or other solvent, may not materially raise general body concentration but may induce anesthesia. It is therefore important to know peak as well as average vapor concentrations.

The curves in Figure 2 below illustrate the differences in rate of absorption by inhalation, and in approach to equilibrium in the circulating blood for different

[13] Private communication from R. W. McKee.

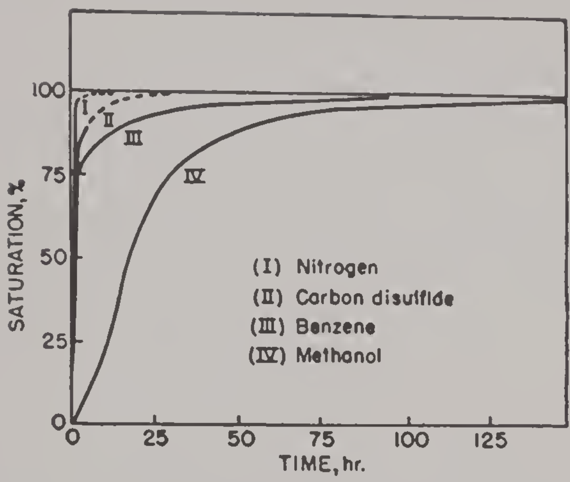


FIG. 2. Curves illustrating the absorption of some representative gases and vapors into the blood of living dogs.

classes of gases and vapors. Nitrogen, nonreactive and slightly soluble, but with some specific affinity, approaches equilibrium rapidly. (See also page 144.) Carbon disulfide, moderately reactive and slightly soluble, approaches saturation rapidly, but data are lacking on the period of complete saturation. Benzene, very slightly reactive and slightly soluble reaches 70 per cent saturation rapidly but does not attain complete equilibrium even after a period of 3 days. Methanol, a slightly reactive, highly soluble vapor, gradually approaches saturation, requiring about 24 hours for 70 per cent saturation and about 5 days for essentially complete saturation. Ethanol (not shown) attains saturation slightly more slowly than does methanol because it is metabolized fairly rapidly.

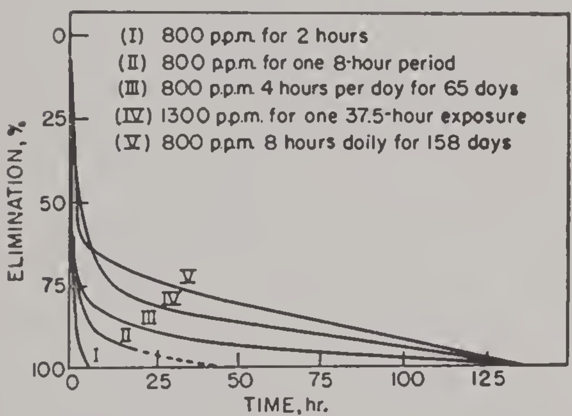


FIG. 3. Curves illustrating the *elimination of benzene* from the blood of dogs after varying degrees of inhalation exposures.

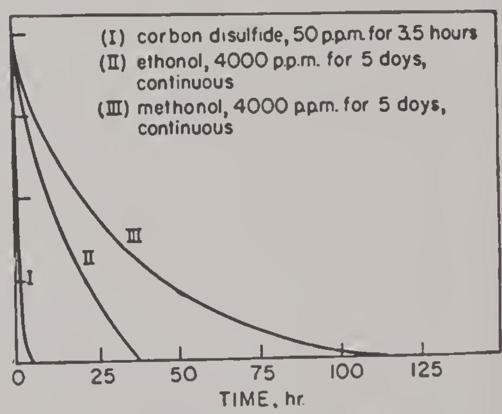


FIG. 4. Curves illustrating the elimination of carbon disulfide, methyl alcohol, and ethyl alcohol from the blood of dogs after inhalation exposures.

Figure 3 illustrates the relative rates of elimination for benzene after exposures for varying lengths of time. These curves indicate that the more severe the exposure to benzene, especially as regards the time factor, the more slowly is it eliminated from fatty reservoirs.

Figure 4 pictures the elimination of carbon disulfide after a brief single exposure to a low concentration, as well as typical elimination curves for ethanol and for methanol. Ethanol is more readily eliminated than methanol because rapid oxidation augments the elimination by expired air, while, as has been pointed out by

Haggard and Greenberg,[14] over 70 per cent of the methyl alcohol is eliminated in the expired air.

3. Effect of Intermittent Exposures

What is the effect of repeated eight-hour exposures, each followed by a sixteen-hour period in uncontaminated air? Dogs have been so exposed to 500 p.p.m. methanol.[15] Absorption ranged from 10 to 20 per cent of saturation in the eight-hour period, and was followed by 50 to 100 per cent desaturation. This resulted in erratic pictures in which some animals gradually accumulated methanol to the extent of 52 per cent of saturation for the particular air concentration (52 per cent of the amount that could accumulate from a continuous exposure). From this high degree of saturation they gradually excreted until they again reached a low level of less than 20 per cent of saturation. Exercise or increased activity greatly speeded this change in either direction, but appeared to have no definite effect upon the direction.

In intermittent exposures to 800 p.p.m. benzene, the blood of dogs exposed 2 hours per day reached an average of about 60 per cent of saturation at the end of exposure, and the animals eliminated 82 per cent of this during the ensuing 22 hours. With a 4-hour daily exposure, the blood reached about 85 per cent saturation and the animals eliminated an average of 85 per cent of this within the following 20 hours. With a daily exposure of 8 hours, the blood reached an average saturation of 92 per cent, while elimination in the ensuing 16 hours was only 76 per cent of this. This frequently resulted in the animals apparently reaching complete saturation, from which high level they would again recede.

With a highly water-soluble vapor, methanol, we see then that from daily 8-hour exposures the vapor may accumulate over a period of time to as much as five times the amount resulting from a single 8-hour exposure, but it never reached more than about half the amount that could result from a continuous exposure, which is a function of the coefficient of distribution for that particular vapor. With a water insoluble vapor such as benzene, however, there is relatively little accumulation, and the concentration of benzene in the blood is largely proportional to the concentration just having been inhaled at any time.

4. Relative Concentrations of Vapor in Blood, Tissues, and Expired Air

We have seen how the concentration of a vapor in the blood is controlled by the concentration of vapor in the inspired air, the length of exposure, and the solubility of the vapor in blood. Let us consider the concentrations of vapor in the tissues, the body fluids other than blood, and the expired air, and how they are controlled. Henderson and Haggard[16] state that the concentration of any vapor in the urine is regulated by the concentration in the arterial blood passing through the kidney at

[14] H. W. Haggard and L. A Greenberg, *J. Pharmacol.*, **66**, 479 (1939).

[15] R. R. Sayers, W. P. Yant, H. H. Schrenk, J. Chornyak, S. J. Pearce, F. A. Patty, and J. G. Linn, *U. S. Bur. Mines, Repts. Investigations* No. **3617** (1942).

[16] Y. Henderson and H. W. Haggard, *Noxious Gases.* 2nd ed., Reinhold, New York, 1943.

the moment of secretion, differs from the concentration in the blood only by the ratio of solubilities of the vapor in the two fluids (approximately 1 : 1 for most vapors), and is a composite of the varying concentrations over the period during which it is secreted. This relation would be expected from the standpoint of physics and appears to hold true for several vapors, but the concentration of benzene in the urine averaged 20 times that in the blood.[17] This concentration has not been explained and certainly cannot be on the basis of the solubility ratio of benzene in blood and urine, but would seem to indicate that the kidneys have the power to extract benzene from the blood in circulation.

For the tissues in general, the relative amounts of a vapor they contain at equilibrium are directly proportional to the solubility of the vapor in the various tissues, but tissues with the greater blood supply and lower solvent capacity saturate, or reach equilibrium, before the tissues of higher solvent capacity and lower blood supply. Likewise these same tissues with the greater blood supply and lower solvent capacity desaturate more rapidly.

The concentration of vapor in the alveolar air during accumulation, equilibrium, or desaturation regulates the concentration of vapor in the arterial blood leaving the lungs at the moment, and therefore can be used as an indication of arterial blood concentration. At complete saturation the vapor concentration in the alveolar air is the same as that in the room air, with due correction for temperature and humidity. With the more soluble vapors, alveolar air concentration, at any point during accumulation, may be used to estimate the average room-air concentration, given the length of exposure, the saturation curve for the particular vapor, and its coefficient of distribution. An interesting variation, of much practical usefulness, is met in the case of radon: its concentration in the alveolar air may be used as an indication of radium storage or deposition, providing sufficient time has elapsed for relatively complete desaturation (8 hours or more after the end of an inhalation exposure).

D. DUSTS AND FUMES

1. *The Absorption of Particulate Matter*

Dusts, fumes, and smokes represent solid particulate matter differing in quality, form, and particle size. The process of their accumulation, distribution, and elimination is much more complicated than the same process with gases. Brown[18] shows that with a number of dusts having a particle size range of 0.25 to 6.0 μ, approximately 55 per cent of the inhaled dust was retained by men. The extremes of retention reported, however, ranged from 15 to 95 per cent. Retention was found to be inversely proportional to the rate of respiration and minute ventilation for rates below 20 inhalations per minute, with no apparent change above 20. Retention was directly proportional to the size of particles or their aggregates, to density, and to wettability. Of this retained dust, a part is retained in the nasal filter and part by contact

[17] H. H. Schrenk, W. P. Yant, S. J. Pearce, F. A. Patty, and R. R. Sayers, *J. Ind. Hyg. Toxicol.*, **23**, 20 (1941).

[18] C. E. Brown, *J. Ind. Hyg. Toxicol.*, **13**, 293 (1931).

with wet surfaces in the respiratory passages, while some reaches the respiratory tissues. The upper respiratory passages are subject to brief periods of low velocity, or static air, between alternately directed flows of rather high velocity air. Because of sharp changes in direction some dust, especially the larger particles, 5 to 20 μ in diameter, are impinged and arrested in these passages by contact with moist surfaces. In the alveoli the air must necessarily be static or moving slowly during respiratory movements, so that ample opportunity is presented for settling and for contact with the moist alveolar walls. If particles are caught before they enter the alveoli, they are continually swept toward the mouth by the ciliated epithelium,[19] which extends from the lower pharynx to the respiratory bronchioles. These ciliated cells are abundant in the trachea, and even more abundant in the large bronchioles, but are sparse in the respiratory bronchioles, and absent in the alveoli. The motions of the cilia are wavelike and their efficiency in propelling mucous and foreign material toward the oral cavity is of a high order. The individual cilium moves toward its goal with whiplike motion, then slowly resumes its former position. It is evident, then, that dust particles trapped anywhere short of the alveolar ducts are subject to removal from the lungs through ciliary action. Upon arrival at the oral cavity they are expectorated or swallowed. Dust particles (silica) reaching and remaining in the alveoli are believed to be largely limited to the sizes ranging between 3 and 0.1 μ,[20] 3 being the largest to arrive at the alveoli in significant quantities. The majority of particles below 0.1 μ are thought to be too small to be trapped in the alveoli and are exhaled much the same as is an undissolved gas. The particles caught in the alveoli may be absorbed through the alveolar wall, or they may be engulfed in phagocyte cells and be carried into the blood capillaries, or enter the lymphatics and be concentrated at the tracheobronchial lymph nodes. Particles of silica 1 μ and under are the most active and dangerous, not only in their ability to remain suspended in the air, but especially in their activity in tissue.[21]

2. Action of Suspended Particulate Matter

The toxic dusts may dissolve and enter the circulation by absorption from the respiratory tract or they may be absorbed after being swallowed. The action of these is discussed under the material involved. "Pneumoconiosis"-producing dusts may exert their effects after lodging in the alveoli. Other particulate matter may cause allergic reactions or, in the case of disease germs, infections. For a complete discussion of the role of dusts and the evaluation of disability arising therefrom see Chapter 15.

E. MISTS

Mists may be inhaled to reach all parts of the lungs and from there may be absorbed. Of a slightly volatile material, concentrations far above those possible from

[19] C. H. Best and N. B. Taylor, *The Physiological Basis of Medical Practice*. 3rd ed., Williams & Wilkins, Baltimore, 1943.

[20] L. U. Gardner, *Ind. Med.*, **9**, 45 (1940).

[21] B. D. Tebbins, R. Z. Schulz, and P. Drinker, *J. Ind. Hyg. Toxicol.*, **27**, 199 (1945).

partial pressures of the gaseous phase at room temperature may be encountered. For that reason a solvent, the vapors of which may be considered harmless at ordinary temperatures can be very dangerous as a mist.

F. OTHER MEANS OF ABSORPTION

1. Ingestion

Ingestion of toxic materials has been mentioned above as resulting from inhalation. It may result from many other sources such as contaminated food, tobacco, or beverages, or from putting fingers or other contaminated objects into the mouth, or from licking the lips. Compared with inhalation, ingestion plays a minor role in the absorption of most toxic materials in industry. However, progressive companies realize that occupational diseases can occur from the careless use of contaminated workrooms as a place in which to eat lunches—all too often without previously washing the hands.

2. Absorption through the Skin

Many gaseous and liquid materials are absorbed to a limited extent through the intact skin by way of the air spaces in the hair follicle to the sebaceous glands and the gland cells. Similarly, according to Rothman,[22] any substance may, through the sweat gland ducts, reach the secretory surface of the sweat gland cells after having passed the straight and the convoluted part of the ducts.

Most electrolytes and water do not penetrate the skin in significant amounts. Alkaloids, phenols, oxalic and salicylic acids and esters, lead acetate, and lead oleate are absorbed in appreciable amounts. Salts of lead, tin, copper, arsenic, bismuth, antimony, and mercury are said to penetrate by combining with the fatty acid radical of the sebum. Ammoniated mercury, however, is said not to be absorbed through the skin as such.[22] Nicotine, strychnine, and opium are absorbed readily, but their salts are not. Slight amounts of hydrogen sulfide and rapidly dangerous amounts of hydrogen cyanide may be absorbed from contaminated air. Nitrobenzene, dinitrobenzene, nitrotoluene, dinitrotoluene, (probably trinitrotoluene), aniline, dimethylaniline, and nitroglycerin are readily absorbed from skin contact with these materials or their solutions. Hodge and Sterner[23] have shown that triorthocresyl phosphate is absorbed through the skin. Alcohols, aldehydes, and acetone are said to be readily absorbed, but from a practical viewpoint there seems to be little significant hazard from this source. Benzene, toluene, xylene, the chlorinated hydrocarbons, and other fat solvents are absorbed to a degree, but the quantities of these materials accumulated in the body in this manner are probably not of a significant order. Tetrachloroethane and other unusually toxic solvents may be exceptions to this statement. Absorption through lesions of the epidermis is much more rapid than through the intact skin.

[22] S. Rothman, *J. Lab. Clin. Med.*, **28**, 1305 (1943).
[23] H. C. Hodge and J. H. Sterner, *J. Pharmacol.*, **79**, 225 (1943).

IV. Standards of Physiological Response

In order to facilitate the comparison of data on the physiological response to the inhalation of atmospheric contaminants, many investigators have tabulated their data in degrees of response such as the following:

Amount producing detectable or other degree of odor
Amount producing detectable or other degree of irritation
Maximum amount for repeated daily 8-hour exposures without injury
Maximum amount for a single 8-hour exposure without serious disturbance
Maximum amount for a single 1-hour exposure without serious disturbance
Amount dangerous to life within several (4 to 8) hours
Amount dangerous to life within ½ to 1 hour
Amount causing death within a few minutes

Levels set for industrial practice have been variously labeled as maximum safe concentration, maximum allowable concentration, toxic limit, maximum permissible concentration, and maximum safe practice. What is, of course, the most desired value is the maximum concentration to which an individual may be exposed throughout his or her working day, for an indefinite period of time, without suffering any ill effects. Unfortunately this has been established satisfactorily for extremely few single substances. The human body is fortified with a defense, or detoxication, mechanism able to cope with all toxic materials in amounts below a certain level, called the threshold of intoxication. So long as this threshold of daily intake is not exceeded, there are no harmful effects, but as soon as this level is exceeded, injurious effects result. This level is not a definite and fixed point for any material, and it may vary not only with individuals, but also with bodily conditions of the same individual. There are many degrees or shades of toxicity among the materials encountered in industry, as for instance the volatile solvents. All of these are toxic if absorbed into the system in excess, their toxicity being a matter of degree, and none of them meriting the classification "nontoxic." How are we to set permissible or safe standards of air contamination for industry?

With very few exceptions all of our so-called "safe" limits are guesses. At their best they are estimates rather than actual safe limits. They are limits set after careful consideration of available toxicity data, largely obtained from exposure of animals, which further research or experience may or may not substantiate. Why then pretend that we know the maximum safe limit unless, as is true for carbon monoxide and other asphyxiants, lead, mercury, and possibly a few other materials, we have the data to establish the point? Even with the asphyxiants we perhaps are not positive of the effects of prolonged inhalation of concentrations too low to cause unconsciousness, and regarding the safe limit for lead, some evidence points to a need for specifying the physical state and chemical combination of the lead. It seems logical that we should, as a guide to the uninitiated, and a check upon the alarmist, and possibly the unscrupulous, without undue delay, set suggested maximum concentrations for materials as soon as, if not before, they attain industrial importance. We should call them suggested maximum concentration standards until we learn through experience, or research, the true maximum safe limit, and then, if necessary, change our standards accordingly.

V. Standards for Permissible Atmospheric Contamination and How They Are Set

Our present standards of practice regarding atmospheric contaminants are very helpful bench marks, as long as we regard them for what they are and do not try to set them up as absolute safe limits, to be regarded as established facts comparable to, or in the same class with inflammable limits, flash points, or other properties that can be determined accurately. Rather, the idea should be fostered that the limits are flexible and are to be adjusted to conform with any new, properly weighted, evidence of facts regarding physiological effects. It must also be remembered that just as all of us are subject to occasional ill health regardless of our work environment, so are we at one time more easily affected by foreign materials than we are at another. There are probably too many uncontrollable factors for us to set a positively safe limit, applying to all people at all times, and still have the limit appreciably different from that of pure air. No matter how carefully our standards are established, if they are maintained at a level compatible with industrial practice, there may be occasional ill health in the especially susceptible individual. We shall always need periodic medical examinations by thorough and competent physicians.

The United States Public Health Service has been the outstanding contributor to our knowledge of maximum permissible limits for atmospheric contaminants, and some of the States have co-operated in the toxicological and chemical studies required to establish such limits. The United States Bureau of Mines, the United States Department of Labor, and a few universities and other schools of higher learning, as well as private research organizations, have added to the store of information.

Some of the States have set up "safe" standards of their own; and, of these standards, some have developed into safe practice codes enforceable by law, but for the most part they have been restricted to advisory standards. A survey conducted by the author in 1943, including thirty-four States, revealed the range of figures adopted by these States as maximum safe concentrations that is shown in Table 2. The wide variation in some figures indicates the need for a central advisory body, whether it be the United States Public Health Service, the American Standards Association, the American Industrial Hygiene Association, or other qualified and representative body with a broad and unbiased interest in the subject, to take the initiative in establishing maximum permissible concentrations. This undesirably wide variation clearly indicates that in some States unqualified men have been responsible for the establishment of schedules that in some instances may be unnecessarily strict, while in others are obviously dangerously misleading in their leniency. Laws and their enforcement are State prerogatives, but toxicity does not vary with locations, and all States should conform to the same pattern of permissible concentrations, based upon all available toxicity data.

The American Standards Association has for the past several years been attempting to establish itself as the authority for the fixing of standards for health and safety, and in 1936 it set up an advisory committee, which was reorganized in 1938

TABLE 2

Range of Permissible Air Pollution as Proposed by Individual States—1943

I. GASES AND VAPORS

Contaminant	Maximum permissible concentration (p.p.m.)		
	Lowest	Highest	Generally accepted
Acrolein	1	3.3	1
Acrylonitrile (vinyl cyanide)	20	20	20
Acetone	200	1000	—
Aliphatic acetates	200	1000	400
Ammonia	50	100	100
Aniline	5	7	5
Arsine	1	30	1
Amyl alcohol	55.6[a]	—	—
Benzene	75	100	100
Bromine	0.15	1	1
Butyl alcohol	100	200	200
Carbon dioxide	5000	5500	5000
Carbon disulfide	15	322	20
Carbon monoxide	100	100	100
Carbon tetrachloride	40	100	100
Chlorine	1	5	1
Chloroform	75	100	100
Cellosolve (monethyl ether of ethylene glycol)	—	500[a]	—
Cyclohexane	150	9300	—
Cyclohexanol	75[a]	—	—
Cyclohexanone	50[a]	—	—
Dichlorobenzene	75	75	75
Dichlorodifluoromethane	100[a]	—	—
Dichloroethyl ether	15	15	15
Dichloromethane	200[a]	—	—
Dichlorotetrafluoroethane	—	140,000[a]	—
Dimethyl aniline	5	5	5
Diethylene dioxide (dioxane)	—	1000[a]	—
Ethanol	250	1000	—
Ether (diethyl)	400	500	400
Ethyl bromide	1700	1700	1700
Ethyl chloride	70	20,000	—
Ethylene dichloride	100	100	100
Ethyl iodide	—	1500[a]	—
Ethylene oxide	250[a]	—	—
Ethyl benzene	—	1000[a]	—
Ethyl silicate	—	500[a]	—
Formaldehyde	10	20	20
Gasoline	500	1000	1000
Hydrochloric acid	10	10	10
Hydrocyanic acid	15	20	20
Hydrofluoric acid	3	3	3
Hydrogen sulfide	20	20	20
Methyl ethyl ketone (butanone)	—	1500[a]	—
Methanol	100	300	200
Methyl bromide	30	100	—

TABLE 2 (1. GASES AND VAPORS)—*Continued*

Contaminant	Maximum permissible concentration (p.p.m.)		
	Lowest	Highest	Generally accepted
Methyl chloride	500	500	500
Methyl cyclohexane	75[a]	—	—
Methyl cyclohexanone	50[a]	—	—
Methyl formate	—	1500[a]	—
Methyl iodide	30	53	—
Monochlorobenzene	75	75	75
Monochloroethylene	—	5000[a]	—
Mononitrotoluene	5	5	5
Methyl Cellosolve (monomethyl ether of ethylene glycol)	25[a]	—	—
Nitric acid	—	10–40[a]	—
Nitrobenzene	1	40	5
Nitrogen dioxide	10	70	40
Nitroglycerin	—	10–40	—
Ozone	0.1	1	1
Pentachloroethane	2[a]	—	—
Petroleum vapors (nonaromatic)	500	5000	1000
Phosphorus trichloride	0.7[a]	—	—
Phosgene	1	1	1
Phosphene	1	2	2
Sulfur dioxide	10	10	10
Sulfuric acid	2[a]	—	—
Tetrachloroethane	10	10	10
Tetrachloroethylene	100	200	200
Toluene	100	200	200
Trichloroethylene	100	200	200
α-Trichloroethane	—	200[a]	—
β-Trichloroethane	—	200[a]	—
Trichlorofluoromethane	—	10,000[a]	—
Turpentine	200	700	200
Vinyl chloride	—	500[a]	—
Xylene	100	200	200

as a working committee to "determine, establish, and promulgate the allowable concentration limits of harmful gases, vapors, fumes, dusts, and mists." The relatively small number of standards for air contaminants that have been set by this body in the ensuing time is an indication of the magnitude of the task and suggests the necessity for a change of policy. This committee includes several recognized, competent authorities in the field of industrial toxicology, and also represents a good cross section of government and business. There is much to be said in favor of such a body, but there are also pitfalls to be avoided. As long as the committee remains large, although it may be cumbersome, there is safety in numbers, and the large cross section of opinion may be relied upon to prevent the group from going too far astray. The most important precaution is that standards set by estimation, as

TABLE 2—*Concluded*

II. DUSTS, FUMES, ETC.

Contaminant	Maximum permissible concentration		
	Lowest	Highest	Generally accepted
Dusts, million particles/cu. ft.			
Asbestos	5	5	5
High silica (above 50%)	5	10	5
Medium silica (5–50%)	5	50	5
Low silica (below 5%)	5	100	50
Nuisance dusts	40	100	50
Talc and soapstone	15	100	15
Slate	15	100	—
Mica	15	100	—
Carborundum	15	100	—
Emery	50	100	—
Alundum	15	100	—
Silicates	15	100	—
Fumes, etc., mg./10 cu. m.			
Cadmium	1	1	1
Arsenic	1.5	5	—
Chromate or dichromate dust	1	1	1
Chromic acid (CrO_3)	1	5	1
Fluoride	10	25	[b]
Iron oxide	100	300	—
Lead	1.5	1.5	1.5
Mercury or Hg vapor	1	4	1
Manganese	50	500	60
Magnesium oxide	150	300	150
Zinc oxide	100	150	150
Barium peroxide	5	5	5
Chlorodiphenyls	0.1	10	10
Chloronaphthalene	5	50	10–50
Dinitrotoluene	15	15	15
Tetryl	15	15	15
Trinitrotoluene (TNT)	15	15	15
Nicotine	—	50–300[a]	—
Radioactive Gases, curie/liter			
Radon gas	10^{-11}	10^{-11}	10^{-11}
Thoron gas	10^{-11}	10^{-11}	10^{-11}

[a] Proposed by only one State.

[b] No generally accepted standard, one State employed a standard of 0.2 to 0.35 mg. fluorine per kg. body weight.

nearly all of them necessarily must be, should not be considered, or portrayed, as ultimate levels of safety but only as tentative levels, representing the present consensus subject to reconsideration upon presentation of any properly weighted evidence. Another point that must be rigorously guarded against is the overbalancing of the committee in favor of men whose training and real qualifications are in the field of oratory instead of the field of industrial toxicology. The alarmist, or the purist who wants to approach zero concentration of all harmful materials, is not

in sufficient numbers, now, to seriously threaten to upset the proper balance. The opinions of all qualified and experienced men in the field should be sought. It should be remembered that the most thorough and complete toxicological data are useless unless accompanied by competent chemical analysis of the air, and the air samples must have been properly chosen to represent exposures existing during the period in which symptoms or manifestations of harmful effects developed, or were demonstrated to be absent.

Chapter Eight

Sampling and Analysis of Atmospheric Contaminants

FRANK A. PATTY

In this chapter the problems involved in sampling and analyzing air contaminants are discussed from a general viewpoint with little regard for individual contaminants. It is not within the scope of this book to give detailed methods of analysis. A rather complete compilation of such methods[1] has been published previously, and in Volume II of this book outlines of, or reference to, methods of proved worth are given under the discussion of each contaminant. The methods so presented are in no sense to be interpreted as the only good methods, but rather methods that have been found suitable and reliable in practice.

Many analytical methods available to the industrial hygienist have been standardized and simplified until they require little thought or training. On the other hand many seemingly simple tests require a fundamental understanding of solubility, the gas laws, partial pressures, and chemical reactions. In any industrial hygiene department many questions arise that can be answered only by a qualified chemist. The method of analysis to be used will depend upon the nature of the problem at hand rather than upon merely a "standard method." The trend is naturally toward methods that give prompt results with a degree of accuracy suited to the circumstances.

The first rule the industrial hygienist should adopt regarding analytical methods is never to rely upon a method until he has personally tried it out under controlled conditions such as: (*1*) by sampling a synthetic atmosphere from a proportioning apparatus or from a gastight, impervious chamber of sufficient size to permit making and sampling mixtures without introducing significant errors, or (*2*) by introducing a measured amount of contaminant into a device attached to the sampling arrangement in such a manner as to utilize the entire amount, or (*3*) by comparing with a device of proved worth by sampling from a common manifold at constant rate over the same period of time.

In evaluating concentrations of atmospheric contaminants of interest to the industrial hygienist, either extremely small quantities of materials must be deter-

[1] M. B. Jacobs, *Analytical Chemistry of Industrial Poisons, Hazards, and Solvents.* Interscience, New York, 1941.

mined or else provision must be made for sampling a large volume of air. The more toxic gases and vapors are of hygienic importance when found to be present in amounts even less than 1 ml. per cubic meter of air (1 p.p.m.), and many dusts and fumes are of interest in amounts of less than 1 mg. per cubic meter of air. Methods of analysis based upon microchemical technique, especially colorimetry, are frequently preferred because they can utilize a very small sample and thus involve less time and difficulties in sampling.

GASES AND VAPORS

I. Methods Giving Quantitative Results in the Field

A. EVALUATING THE INTENSITY OF ODOR AND IRRITATION

Perhaps the most useful of all methods of detecting and estimating gases and vapors in the air is by their odors and irritant effects. Only a relatively few toxic ones are without either of these characteristics, notable among which is carbon monoxide. Many well-informed persons are inclined to scoff at the idea of considering odor and irritation as qualitative guides, much less quantitative ones, but that is either because they have never cultivated and educated the sense of smell or because for them that sense is physiologically substandard. The particular power of odors to quicken memory of associations has long been recognized. For instance the odor of acetamide instantly calls up for most people the association of mice because it was first met as a constituent of mouse urine; the odor of nitrobenzene is associated with shoe polish because it once was widely used as an ingredient of shoe polish; and there are many others.

There have been various attempts to describe and classify the odor sensations. Henning,[2] in one of the best, recognizes six classes as follows: spicy, flowery, fruity, resinous (turpentine), foul, and scorched. To further divide or add to these classes is a very difficult problem and, even though the memory of an odor may extend over many years, we seem to lack the proper descriptive adjectives. However, regardless of the quality of an odor, Gamble[3] has shown that in conformity with Weber's law the sense reaction to odors is proportional to the logarithm of the stimulus, that is, the intensity of sense reaction increases in arithmetical progression as the stimulus increases in geometrical progression. Katz and Allison[4] devised the following odor and irritation scales, which with slight modification have since proved convenient for other investigators.

Odors are best determined by the first and second inhalations, as succeeding inhalations may tend to fatigue the sense of smell. Nasal irritation, throat irritation, and eye irritation, however, frequently increase with time, at least for the first several seconds and sometimes minutes. During the first attempts to evaluate odor and irritation, a subject may have considerable difficulty in making estimations that

[2] Hans Henning, *Der Geruch*. Leipzig, 1924.
[3] Eleanor A. M. Gamble, *Am. J. Psychol.*, **10**, 82 (1898).
[4] S. H. Katz and V. C. Allison, *U. S. Bur. Mines Tech. Paper* No. **267** (1920).

TABLE 1

Scale of Odor Intensities

Degree	Intensity	Description
0	No odor	No detectable odor
1	Very faint	Minimum, but positively perceptible odor
2	Faint	Weak odor, readily perceptible
3	Easily noticeable	Moderate intensity
4	Strong	Cogent, forcible odor
5	Very strong	Intense effect, may irritate

TABLE 2

Irritant Scale (Nasal Irritation and Eye Irritation)

Degree	Intensity	Description
0	No irritation	Not detectable
1	Faint	Just perceptible, not painful
2	Moderate	Moderate irritation, midway between 1 and 3
3	Strong	Discomforting, painful, but may be endured
4	Intolerable	Exceedingly painful, cannot be endured voluntarily

conform to the pattern of a representative group, but most persons overcome this difficulty rapidly so that with a group of six persons the deviation of individuals from the average is rarely more than one degree on the scale. As has been pointed out, however, some individuals are handicapped by having an impaired sense of smell; and likewise, temporary impairment of anyone's sense of smell may result from various causes. Additional published data[5–8] on odor intensities is inadequate, and therefore the problem more or less resolves itself into a matter of individual education, and industrial hygienists find it advantageous to note and record the quality and intensity of odors wherever an evaluated atmospheric contaminant is either encountered or prepared.

The graphs reproduced here are portrayals of data collected from experiments in synthetic atmospheres, where 4 to 7 investigators kept independent notes. Each point on the graph is an average of the individual results. Figure 1, prepared from data collected by the United States Bureau of Mines[9] showing the relation between odor intensity and concentrations of allyl mercaptan and ethyl mercaptan, illustrates, on the part of allyl mercaptan, an irregularity or departure from Weber's law. Benzyl mercaptan, not shown, has a similar tendency except that the odor intensities below 3 appear to conform to a curve rather than to a straight line. The same is true of commercial heptane and hexane portrayed in Figure 2. Figure 3 portrays

[5] *International Critical Tables*, Vol. *1* (1926).

[6] S. H. Katz and E. J. Talbot, *U. S. Bur. Mines Tech. Paper* No. **480** (1930).

[7] A. C. Fieldner, R. R. Sayers, W. P. Yant, S. H. Katz, J. B. Shohan, and R. D. Leitch, *U. S. Bur. Mines Monograph* No. *4* (1931).

[8] F. A. Patty and W. P. Yant, *U. S. Bur. Mines Repts. Investigations*, **2978** (1929).

[9] S. H. Katz and E. J. Talbot, *U. S. Bur. Mines Tech. Paper* No. **480** (1930).

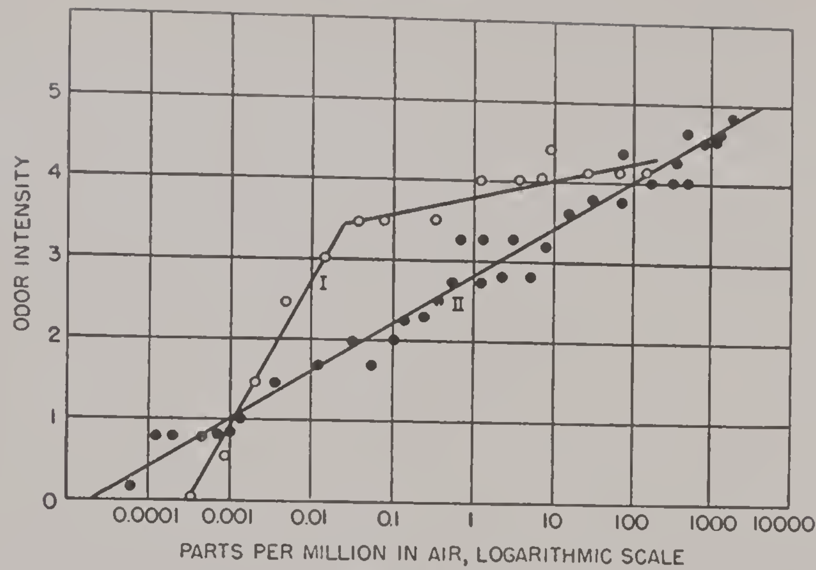


FIG. 1. Odor intensity in relation to concentration of vapors of allyl mercaptan (I) and ethyl mercaptan (II).

results with the same materials, as in Figure 2, after they had been treated to remove traces of sulfur compounds. The heavy, solid, "intermittent exposure" lines represent the odor impression upon the first complete inhalation; while the dotted lines represent the impression obtained by remaining in the atmosphere while the concentration was being built up over several minutes.

Although the odor and irritation method of locating and evaluating exposures is very useful, its limitations are obvious: it offers no record, the sensitivity of the sense of smell varies with individuals, and the sense fatigues rapidly. Near the source of a toxic vapor the concentration in the air may be high, but it falls rapidly as the distance from the source increases. Thus an industrial hygienist, walking through a plant on a tour of investigation, may go through a low concentration with little or no warning odor, and by the time the area of moderately high concentration is reached fatigue may have occurred to an extent that would cause the vapor to be grossly underestimated or missed entirely. When the odor in a suspected area is being checked it may prove advantageous to enter it rapidly from uncontaminated air, holding the breath if necessary until the sampling zone is reached, then estimating the intensity of odor on the first inhalation. If the odors and irritant effects of atmospheres are used as guides, they can be so used to tremendous advantage, but they should never be proposed as accurate or acceptable means of analysis. A trained man, in estimating the concentration of an odorous or irritant vapor or gas, is not likely to estimate less than 1/3 nor more than 3 times the amount actually present: that is, if a trained investigator estimates by the odor a concentration of hydrogen cyanide to be 6 p.p.m., for instance, he can be reasonably certain the actual concentration is not below 2 p.p.m. nor above 18 p.p.m. This degree of accuracy is satisfactory in certain situations and entirely unsatisfactory in others.

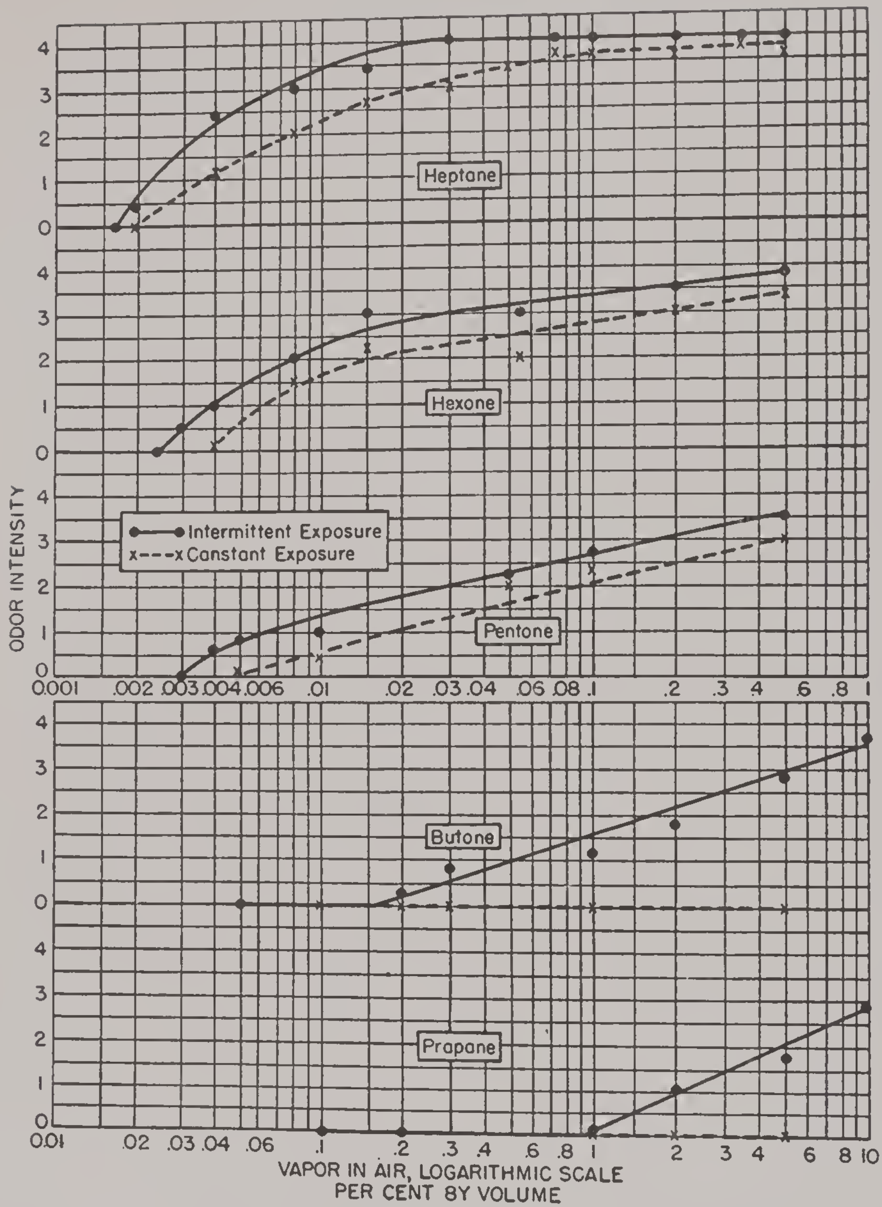


FIG. 2. Relation between concentration of vapors of commercial paraffin hydrocarbons and odor intensity.

B. PORTABLE RAPIDLY INDICATING DEVICES

Nearly all physical sampling methods are open to the same criticism: they are not specific, and it is sometimes impossible to tell whether the physical changes measured, especially small ones, are due to the presence of a particular gas or vapor or to some other cause; and in mixtures it is not always feasible to determine the percentage of each component. The advantages, however, of portability and immediate availability of results make some physical instruments immensely useful.

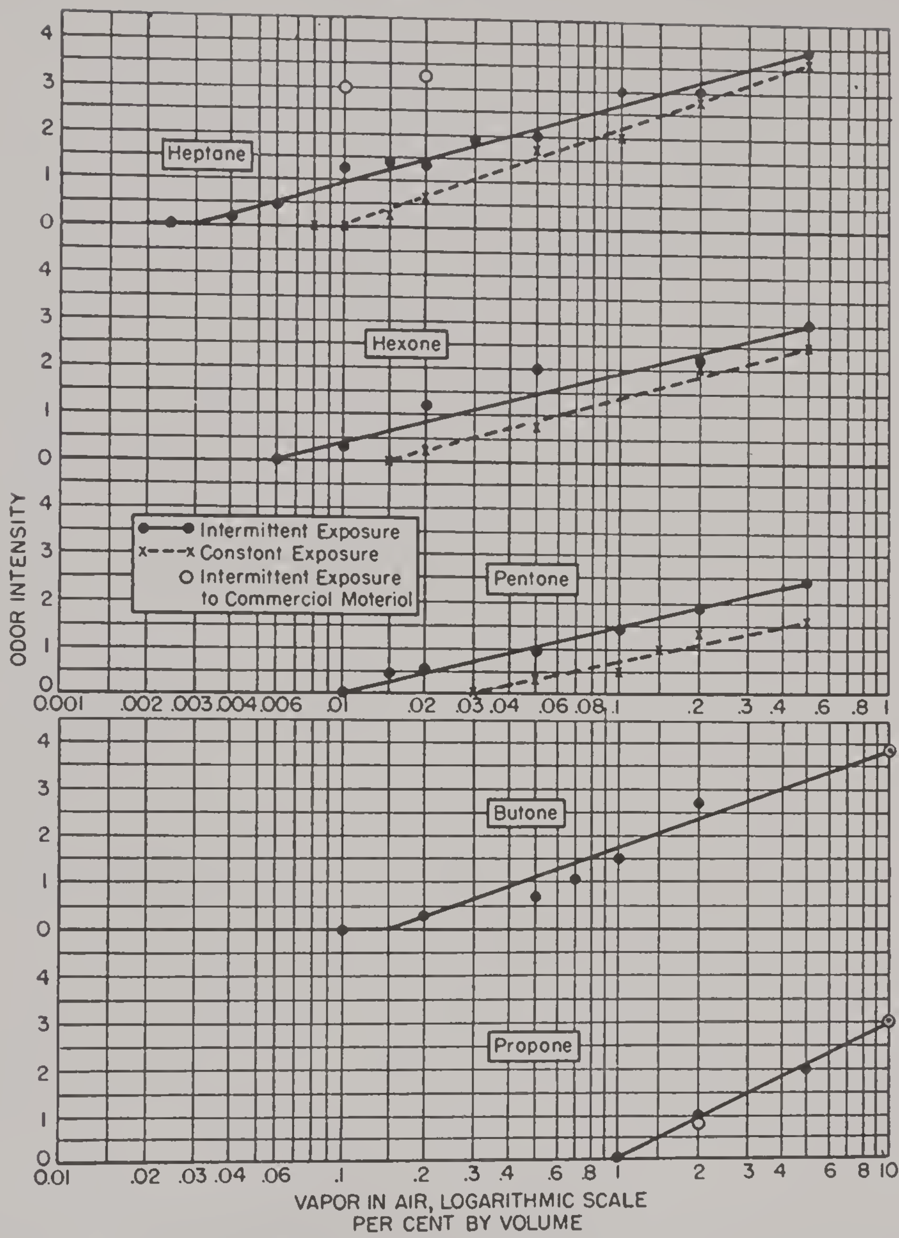


FIG. 3. Relation between concentration of vapor of purified paraffin hydrocarbons and odor intensity.

1. *Interferometer*

Perhaps the most dependable and most widely applicable physical instrument yet developed for field use is the 50-cm. portable gas interferometer. This instrument accurately measures minute changes in refractivity, so that it may successfully be used to determine low concentrations of contaminating gases or vapors in the atmosphere, providing the refractivity of the contaminant is sufficiently different from

that of air, which is 291.7×10^{-6} at 0° C. and 760 mm. Hg pressure. Since refractivity is a function of density, as well as of molecular structure, slight changes in pressure and temperature have an important bearing on results and must be carefully controlled. The light source must be of constant wave length and is usually an incandescent filament. The interferometer is a sensitive form of refractometer which, instead of measuring refraction directly, compares the refractivity of one gas to that of another. In air analysis, the usual standard of comparison is dry air, from which all carbon dioxide has been removed. This standard atmosphere must be at the same temperature and pressure as the atmosphere to be examined. An interferometer may be calibrated against known mixtures of vapor in air, of the same order of concentration as atmospheric mixtures in which it is to be employed. Also, it may be calibrated for absolute refractivity changes, that is, refractivity factor, by increasing the pressure of dry air in one cell, referred to similar dry air at constant atmospheric pressure in the other.[10, 11] Once this refractivity calibration has been accomplished, instrument scale readings may be translated to vapor percentages by employing any reliable data on the refractivity of vapors and gases. These data are perhaps most readily utilized when presented as unit refractivity change ($U\Delta R$), i.e., the change

TABLE 3

Unit Refractivity Change, $U\Delta R$

Solvent	$U\Delta R \times 10^6$	Solvent	$U\Delta R \times 10^6$
Methyl alcohol	2.5	Heptane	19.2
Ethyl alcohol	5.4	Octane	22.7
n-Propyl alcohol	8.6	Cymene	25.9
n-Butyl alcohol	11.6	Cyclohexane	15.1
Amyl alcohol	14.3	Cyclohexene	14.4
Methyl amyl alcohol	16.7	Cyclohexanol	15.4
Ethyl formate	8.7	Cyclohexanone	13.7
Ethyl acetate	11.6	Methyl cyclohexane	17.5
n-Butyl acetate	18.0	Methyl cyclohexanone	16.3
Amyl acetate	20.4	Benzene	14.4
Ethyl propionate	14.7	Toluene	17.5
Furfural	13.1	Xylene	20.4
Acetone	7.6	Ethylbenzene	20.1
Butanone	10.2	Pyridine	12.7
Pentanone	13.1	Chloroform	11.3
Hexanone	16.1	Carbon tetrachloride	14.6
Hexone	16.6	*s*-Dichloroethylene	10.8
Heptanone	19.0	Trichloroethylene	13.7
Octanone	21.9	Tetrachloroethylene	16.9
Mesityl oxide	16.3	Ethylene dichloride	11.1
Isophorone	19.2	Propylene dichloride	13.6
Ethyl ether	11.9	Dichloroethyl ether	16.9
Isopropyl ether	17.8	Chlorobenzene	17.5
n-Butyl ether	23.0	Ethyl bromide	9.5
Cellosolve	11.6	Ethylene bromide	14.3
Dioxane	11.3	Ethyl iodide	12.8
Pentane	13.4	Carbon disulfide	11.3
Hexane	16.6	Water	−0.28

[10] J. D. Edwards, *U. S. Bur. Mines Tech. Paper* No. **131** (1919).
[11] F. A. Patty, *J. Ind. Hyg. Toxicol.*, **21**, 469 (1939).

in the refractivity of dry air at 25° C. and 760 mm. Hg pressure due to the admixture of 1 per cent gas or vapor. The data given in Table 3 were obtained by vaporizing weighed amounts of solvents in a galvanized metal chamber having a volume of 604 cu. ft.

The concentration of a known vapor may be determined as follows:

$$\text{percentage vapor in air} = \frac{\text{interferometer reading} \times \text{refractivity factor (of instrument)}}{\text{unit refractivity change (of vapor)}}$$

For example, in measuring benzene vapor, suppose the interferometer scale reading is increased 62 divisions or 0.62 revolution of the indicator dial above its reading in "fresh" air and each revolution is equivalent to a change in refractivity of 2.91×10^{-6}, the percentage of benzene would equal:

$$\frac{0.62 \times 2.91 \times 10^{-6}}{14.4 \times 10^{-6}} = 0.125 \text{ (1250 p.p.m.)}$$

The refractivity of a mixture of vapors is the sum of the refractivities of the components. Water vapor gives a negative reading and if it has not been removed from the atmosphere to be sampled, any difference between the humidity of the atmosphere in which the zero point was set and the atmosphere to be sampled must be measured and taken into account.

2. *Portable Orsat*

The portable Orsat[12] consists of a 100-ml. gas burette and four pipettes: one containing sodium hydroxide, one alkaline pyrogallate, one acid cuprous chloride solution, and the fourth being a slow combustion pipette for burning combustible gases. The apparatus is suitable for the determination of carbon dioxide, oxygen, nitrogen, methane, and some other combustibles, including carbon monoxide in high concentration. Concentrations of carbon monoxide high enough to be detected with this device are, however, immediately dangerous to life. The limit of accuracy is 0.2 to 0.3 per cent. The chief application of this device is in the analysis of the atmosphere in mines.

3. *Combustion Devices*

Combustible gas indicators. Combustible gas indicators of numerous kinds are available. In the majority of these instruments the atmosphere to be tested is drawn across a platinum filament which is heated by a dry cell. This filament forms one arm of a Wheatstone bridge and is balanced before use against another heated filament in an inert atmosphere. Any combustible gas in the sample drawn across the hot filament is oxidized or burned catalytically, which burning results in an increased temperature of the filament and a consequent increase in resistance to the flow of electricity. The increase in resistance is proportional to the amount of inflammable gases or vapors in the sample and is measured by a meter that has a scale calibrated for certain classes of vapors to give readings directly in percentage of the lower in-

[12] W. P. Yant and L. B. Berger, *U. S. Bur. Mines Miners' Circ.* No. 34 (1936).

flammable limit. The sensitivity of these devices varies from the less sensitive, calibrated in fourths of the lower inflammable limit, to the most sensitive type calibrated to a few p.p.m. These instruments are very useful in locating sources of combustible gases or vapors and in evaluating fire and explosion hazards. One of the most sensitive type is termed a "benzene indicator." All of them should be checked periodically against known mixtures of the vapor to be analyzed.

Carbon monoxide indicators. Carbon monoxide is perhaps most satisfactorily measured by drawing the air to be analyzed, at a constant rate, through Hopcalite, in which sensitive thermocouples are located. The Hopcalite catalyzes the union of carbon monoxide with oxygen to form carbon dioxide, and the heat generated by this reaction is converted to electrical energy by the thermopile and registered by a recording potentiometer or a millivoltmeter.[13] The air to be analyzed must be dried by suitable means, and must be freed of interfering combustible gases by drawing it through an activated carbon filter. Hydrogen, methane, and nitrogen dioxide are not readily removed by this treatment and, if present, will yield high results. Self-contained, portable instruments embodying the above principle are available.[14]

These portable instruments are sometimes subject to significant errors due to variations in humidity and temperature, especially where measurements below 100 p.p.m. are desired. The difficulty of establishing constant zero readings can be lessened by recirculating the air through the instrument. This is especially helpful in cold weather when the air to be measured is warm and the reference air would be cold, or when the reference air is suspected of containing traces of carbon monoxide. Since this instrument is subject to altitude fluctuations also, it is unsuited to measuring low but significant amounts of carbon monoxide in airplanes. A special type of carbon monoxide indicator[15] for this latter purpose, said to be sensitive to 10 p.p.m. and not affected by altitude and temperature changes, has been developed for sale recently.

In all types the Hopcalite is subject to deterioration with use and it, as well as the filter for removing organic vapors and water vapor, must be renewed periodically. These instruments are valuable and dependable when properly maintained, but are completely unreliable unless they are serviced by competent men. It is good practice to calibrate them with a known mixture of carbon monoxide and air either periodically or else before each series of tests. Carbon monoxide–air mixtures may be purchased in cylinders; or the air mixtures may be made as required by metering carbon monoxide and air, each through a venturi-type flowmeter, into a mixing chamber. Carbon monoxide, with a purity of 98 per cent or better, is readily made by dropping formic acid into heated sulfuric acid and passing the gas through soda lime to remove acid vapors. The carbon monoxide thus generated or carbon monoxide purchased in cylinders may be used to make the desired mixtures.

[13] S. H. Katz, D. A. Reynolds, H. W. Frevert, and J. J. Bloomfield, *U. S. Bur. Mines Tech. Paper* No. 355 (1926).

[14] Carbon Monoxide Indicator, Mine Safety Appliances Co., Pittsburgh, Pa.

[15] W. P. Yant, *personal communication.*

Flame safety lamps. Flame safety lamps that have been approved by the United States Bureau of Mines[16] are satisfactory for the recognition and rough estimation of some combustible gases as well as of atmospheres deficient in oxygen.[17] Obviously they must be used correctly in inflammable atmospheres in order to avoid accidental ignition of the atmosphere.[18]

4. Ultraviolet Absorption Devices

Ultraviolet absorption has been used successfully to measure mercury vapor,[19] and more or less successfully for trichloroethylene and some other vapors.[20] If this type of instrument can be developed with variable wave length and sensitivity control, it should prove useful for both qualitative and quantitative air analysis for gases and vapors, and especially so in mixtures of unknown composition. In the device for measuring trichloroethylene, light of a fixed wave length in the ultraviolet range is passed through an absorption cell onto a cell sensitive to ultraviolet light. When air containing vapors having an opacity to light of this wave length is passed through the cell, the depletion of transmission is proportional to the concentration of the vapor, providing the atmosphere is free of dust.

The following is a promising variation, involving analysis in the laboratory. Samples of some solvent vapors, collected by drawing the atmosphere through an especially good grade of granulated silica gel at about 1 liter per minute can be transported to the laboratory in glass-stoppered bottles, leached out with a small amount of methanol and an aliquot evaluated successfully by means of the Beckman ultraviolet spectrophotometer.[21]

C. COLLECTION IN INDICATOR MEDIUM

Certain contaminants may be collected in scrubbers or impingers containing a liquid medium that by change of color serves as an indicator. By this means a predetermined amount of an atmospheric contaminant may be recognized; it is then only necessary to consider the volume of air that has been sampled up to the time of color change in order to estimate the concentration of the material. The accuracy of such methods is usually within the range of 80 to 98 per cent, depending upon the gas sampled and the efficiency of the scrubber. Although not entirely satisfactory for research work, and for the setting of standards of maximum permissible contamination, these methods are particularly useful in informing the industrial hygienist—in the field—of the order of intensity of contamination and therefore whether control is necessary, and if so, to what extent.

As an example of how this may be used to advantage, without adding an im-

[16] J. W. Paul, L. C. Ilsley, and E. J. Gleim, *U. S. Bur. Mines Bull.* No. **227** (1924).

[17] A. B. Hooker, E. J. Coggeshall and G. W. Jones, *U. S. Bur. Mines Repts. Investigations,* No. **3327** (1937).

[18] W. H. Tomlinson, *U. S. Bur. Mines Circ.* **7271** (1944).

[19] T. T. Woodson, *Rev. Sci. Instruments,* **10,** 308 (1939).

[20] V. F. Hanson, *Ind. Eng. Chem., Anal. Ed.,* **13,** 119 (1941)

[21] E. M. Adams, *personal communication.*

practical burden of weight to the field equipment, consider the determination of ammonia or acid gases using the midget impinger, with or without special scrubbers, as the sampling device. The sampling rate must be accurately calibrated. The impinging liquid is water with a measured amount of standard 0.01 *N* acid or alkali containing 0.01 per cent methyl red indicator. The standard reagents can be carried in small glass-stoppered bottles and pipetted into the scrubbers as required. The skill of a chemist is required for making up the standard solutions, but any experienced industrial hygiene engineer, exercising ordinary care, can carry out the sampling technique of loading scrubbers in an uncontaminated atmosphere and noting the operating time required to produce a color change in the collecting liquid. The computation for a sampling rate of 2832 ml. per minute is: 1 ml. 0.01 *N* reagent = 0.2445 ml. monovalent gas at 25° C. and 760 mm. Hg pressure

$$\frac{0.2445 \times 1{,}000{,}000 \times \text{ml. reagent}}{2832 \times \text{minutes}} = \frac{86 \times \text{ml.}}{\text{minutes}} = \text{p.p.m. for gases of one hydrogen equivalent}$$

For gases having two hydrogen equivalents the formula becomes $\frac{43 \times \text{ml.}}{\text{minutes}}$. This has been used successfully for ammonia and most of the common acid gases.

Hydrogen sulfide, sulfur dioxide, and hydrogen cyanide may be determined in a similar manner, employing 0.01 *N* iodine solution and starch indicator. The hydrogen cyanide is collected in a sodium bicarbonate solution containing the iodine; also, the reaction requires one mole of iodine for one of hydrogen cyanide, since each half of the molecule combines with an iodine atom.

$$NaCN + I_2 \rightarrow NaI + CNI$$

Sulfur dioxide and hydrogen sulfide each require only the usual solution of iodine in potassium iodide, and the reactions are the common oxidation ones:

$$SO_2 + 2\ H_2O + I_2 \rightarrow H_2SO_4 + 2\ HI$$
$$H_2S + I_2 \rightarrow 2\ HI + S$$

A similar result is achieved by utilizing the color developed by the solution of the contaminant in the sampling medium. This simple type may be utilized in estimating ammonium picrate. Ammonium picrate in water, with no added reagents, produces sufficient color so that 0.01 mg. in 10 ml. of water is readily distinguishable from none and from 0.02 mg. Each sample is collected until a visible color is obtained and then that color is compared with standards, in the field. (Ammonium picrate, TNT, Tetryl, and other contaminants in their class have been successfully collected by means of the midget impinger regardless of whether they occurred as vapor or particulate matter.) TNT and Tetryl samples may be collected and semiquantitative results may be obtained in the field by the use of diethylaminoethanol[22] in the impinger; but, due to the gradual and continuous development of color for many hours, really satisfactory results must await transportation to the laboratory. However, the use of permanent standards, and possibly an accelerator, would improve the results obtainable at the time of sampling. In its present stage of development

[22] F. H. Goldman and D. E. Rushing, *J. Ind. Hyg. Toxicol.*, **25**, 164, 195 (1943).

the method is satisfactory only in the laboratory, where results may be determined with a spectrophotometer and compared with results obtained with standard solutions, due regard being taken of the time factor.

D. HAND PISTON PUMP, LUER SYRINGE, AND RUBBER-BULB COLLECTION DEVICES

Hand piston pumps and rubber aspirating bulbs have been used for collecting samples. These methods, which aim to avoid the more cumbersome, orthodox methods of sampling, may involve pulling the atmosphere through indicating granules, such as in the M.S.A. hydrogen sulfide detector, and the Hoolamite detector for carbon monoxide. Indicator paper or a scrubber may also be used. The pump may be calibrated and the sample measured by the number of piston strokes. Luer syringes have been used for measuring atmospheric samples and as reaction chambers for the determination of oxygen,[23] and also as a comparison chamber in the determination of nitrogen dioxide.[24] All examples of this class of sampling have as their purpose the keeping of sampling equipment to a minimum and also the obtaining of direct results in the field. Accuracy in some instances may, and in others may not, equal that obtained by longer and more cumbersome methods.

II. Methods Requiring Laboratory Analysis

A. HALOGENATED HYDROCARBONS COMBUSTION APPARATUS

Several devices have been proposed for the combustion of halogenated hydrocarbon vapors in the atmosphere. Passing the atmosphere through a heated tube containing a platinum foil was first utilized by Pregl[25] and several modifications for field use have been made.[26–29] The use of a free flame for the combustion analysis of this class of vapors was introduced by Patty, Schrenk, and Yant.[30] A similar plan was followed by Winter,[31] using a lamp method. A sulfur lamp apparatus was used by Wirth and Stross[32] to determine sulfur and chlorine in gasoline, and since then has been used for the determination of various organic chlorides in inflammable liquids. Elkins[33] scrubbed carbon tetrachloride from the air with amyl acetate and burned it in a modified sulfur lamp. In all of these methods combustion was found to be quantitative. The percentage absorption of the products of combustion varies with the type of apparatus employed and may be seriously low when sampling con-

[23] Y. Henderson and L. A. Greenberg, *J. Am. Med. Assoc.*, **96**, 1474 (1931).

[24] F. A. Patty and G. M. Petty, *J. Ind. Hyg. Toxicol.*, **25**, 361 (1943).

[25] F. Pregl, *Quantitative Organic Microanalysis*. Trans. by Tylemann. 2nd ed., Blakiston, Philadelphia, 1924.

[26] W. M. Malisoff, *Ind. Eng. Chem., Anal. Ed.*, **7**, 428 (1935).

[27] B. D. Tebbens, *J. Ind. Hyg. Toxicol.*, **19**, 204 (1937).

[28] A. N. Setterlind, *Determination of Chlorinated Hydrocarbons (Except Chloronaphthalenes)*. Illinois State Dept. of Health, Div. of Industrial Hygiene, Chicago, Ill.

[29] H. C. Dudley, *U. S. Public Health Repts.*, **56**, 102 (1941).

[30] F. A. Patty, H. H. Schrenk and W. P. Yant, *Ind. Eng. Chem., Anal. Ed.*, **4**, 259 (1932).

[31] P. K. Winter, *Ind. Eng. Chem., Anal. Ed.*, **15**, 571 (1943).

[32] C. Wirth and M. J. Stross, *Ind. Eng. Chem., Anal. Ed.*, **5**, 85 (1933).

[33] H. B. Elkins, A. K. Hobby, and J. E. Fuller, *J. Ind. Hyg. Toxicol.*, **19**, 474 (1937).

centrations on the order of 0.2 per cent or higher, and when using a small volume of absorbing liquid. In the combustion-tube method at least ½ hour is required to collect the sample, after which the combustion products must be washed into a suitable flask and taken to the laboratory for titration, which is simple and rapid. The sulfur-lamp method requires more time since it involves scrubbing the vapor from the air before it can be burned in the lamps. The combustion methods are specific only for the class of halogenated vapors and gases (chlorides, bromides, or iodides), and organic halogens can not be differentiated from acid halogens, unless sampled through a filter to remove acid halogens. Methods employing glass apparatus are not applicable to the determination of fluorides, because the fluoride combustion products attack glass. These combustion methods obviously give an integrated result for the entire period of sampling.

It will be of interest to compare sets of figures obtained independently by two experienced operators, one with the Willson combustion apparatus for halogenated hydrocarbons, and one with the Zeiss gas interferometer. The samples were taken

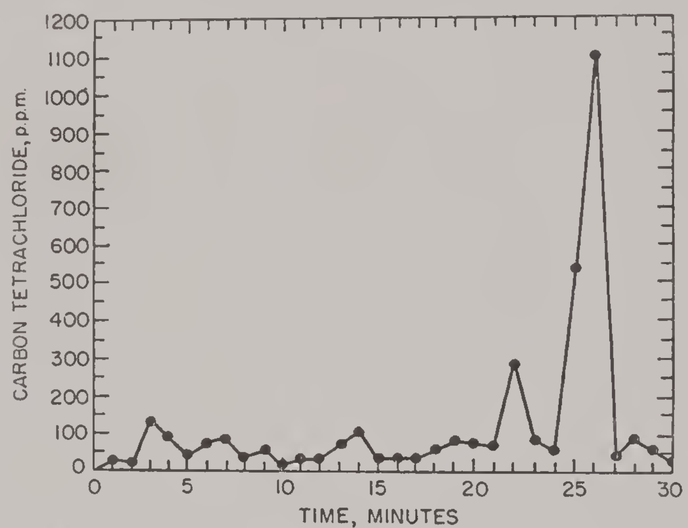


FIG. 4. Carbon tetrachloride vapor in air as determined by means of a gas interferometer.

over a 30-minute period in a room of a plant where carbon tetrachloride was being splashed from bottles onto a table top. The samples were drawn through a 3-ft. glass tube extension on the combustion tube of the Willson apparatus, the extension being provided with a side connection or Y leading to the interferometer. The result obtained with the Willson apparatus was 101.6 p.p.m. carbon tetrachloride. The results obtained with the interferometer, plotted in Fig. 4, average 123 p.p.m., with a minimum of 6 p.p.m. and a maximum of 1096 p.p.m. during the ½-hr. sampling period.

More than one interpretation of this variation in results is possible. It may be that we have here a true measure of the actual difference between the mean of this

series of grab samples and the average obtained from an integrated continuous sample.

At first glance one might say that the difference here of 21 p.p.m. between the two methods is within the experimental error of the interferometer and assume the combustion result to be correct. However, although there is a probable error of 20 p.p.m. for one reading on the interferometer, for a series of readings the result obtained is much closer to the correct one, and probabilities are that the combustion apparatus gave slightly low results,[34] especially for the period of time that the concentration was above 500 p.p.m. The correct result may well be assumed to have been 5 to 15 per cent above the combustion results, or between 107 and 117 p.p.m.

The graph is an interesting illustration of another point, that is, of the futility of trying to evaluate a variable exposure by a single, or even a few, random grab samples. To be reliable the grab samples must be taken at frequent regularly spaced intervals. These particular samples represent an abnormal variation in concentration in that the spillage was frequent and variable, with constantly good general ventilation. Under such conditions, if the chief concern is maximum level of contamination, the industrial hygienist will choose properly spaced grab samples; if toxicity is more dependent upon cumulative exposures, he may prefer the integrated sample.

B. ADSORPTION FOR EVALUATION BY WEIGHT

Many variations of the adsorption method introduced by Greenburg[35, 36] have been proposed by different investigators. The principle is the same in all and the shortcomings are similar. The usual adsorbent is activated charcoal or silica gel confined in convenient weighing tubes. These materials are not selective but readily adsorb most vapors and gases, especially those of high molecular weight. The sample of vapor in air is drawn through the adsorbent at a constant rate, usually 1 liter or less per minute, and after a suitable sample is collected the tube with its contents is weighed. Since practice has shown that variations in weight of silica gel tubes, and even more so of charcoal tubes, often amount to more than 5 mg. within a 24-hour period as a result of static charges, moisture, and other factors, even though no air has been passed through them, it is obvious that dependable results require samples weighing at least 50 mg. If the sample is collected at the rate of 1 liter per minute, and it is desired to determine the concentration of benzene in the air of a room where the average concentration amounts to 50 p.p.m. (0.16 mg. per liter), it is evident that a sampling time of about 5 hours would be required for dependable results. In higher concentrations this method is more applicable, since less time is required to obtain a sample of suitable weight. Tubes equilibrated for several hours in air of the same humidity and temperature as the atmosphere to be analyzed may be used without filters for removing water vapor and carbon dioxide from the air sampled. However, it is the usual practice in the interest of accuracy to employ such filters wherever they do not alter the concentration of the contaminant, and Moskowitz

[34] F. H. Goldman and C. G. Seegmiller, *J. Ind. Hyg. Toxicol.*, **25**, 181 (1943).
[35] L. Greenburg, *U. S. Pub. Health Repts.*, **41**, 1516 (1926).
[36] W. A. Cook and A. L. Coleman, *J. Ind. Hyg. Toxicol.*, **18**, 194 (1936).

and Burke[37] found it advantageous to have filters before and after the adsorbent. The ones ahead of the adsorbent removed water and carbon dioxide from the air, and the ones following the adsorbent collected water and carbon dioxide lost by the adsorbent as the air passed over it. The adsorption method obviously collects an integrated sample, while it is frequently desirable to follow the changes in concentration in order to obtain information on the height and duration of peak values. The method is applicable to gases and vapors of high molecular weight and moderate toxicity. It must always be borne in mind that many vapors cannot be filtered through drying agents and soda lime without partial or even complete loss within those agents. Since the method warrants an accuracy only to the nearest milligram, weighing usually can be accomplished at any laboratory or in the field. Vapor samples adsorbed on activated carbon or silica gel may also be transported to the laboratory, released by passing heated air through the adsorbent, and the vapor determined by suitable chemical methods of analysis. (Refer also to pages 210 and 211.)

C. CONDENSATION AT LOW TEMPERATURES

Most vapors may be collected successfully by drawing them through a suitable chamber immersed in a low-temperature bath, the temperature required being that at which the vapor pressure of the liquid or solid to be collected approaches zero. A metering device for the air mixture is necessary, and the rate must be slow enough to permit condensation and avoid loss of mist or dust of the condensed material. The design of the condensation chamber must be such as to avoid choking with either ice or solid contaminant condensed from the air sampled. The condensed material may be weighed, measured by volume, or determined by quantitative chemical analysis. Ice, solid carbon dioxide, and liquid air have each been employed as the refrigerating medium.

D. COLLECTION BY ABSORPTION OR ADSORPTION FOR LABORATORY ANALYSIS

The collecting device here may be any of several types of scrubbers or impingers, and the collecting medium may be granulated silica gel or a liquid of low volatility, either of which must be a tenacious adsorbent or absorbent for the contaminant or else it must fix the contaminant by chemical combination. The collectors may be used singly or in series depending upon their established efficiency. The collected samples are transported to the laboratory and evaluated by various means, which include colorimetric, volumetric, polarographic, or spectrographic analyses, the use of the ultraviolet or infrared spectrometer, and combustion. (Refer also to pages 208 and 214.)

E. SAMPLING IN EVACUATED BOTTLES

1. Vacuum Bottle Samples

Samples are conveniently collected in vacuum bottles for the determination of oxygen, carbon dioxide, and combustible gases in the analysis of mine gases by

[37] S. Moskowitz and W. J. Burke, *N. Y. State Ind. Bull.*, **17**, 168 (1938).

means of the Haldane[38] or Orsat[39] gas burettes; for the determination of radon by means of especially constructed electrometers (page 266); for the determination of nitrogen oxides by the phenoldisulfonic acid method; and for many other determinations. Usually this type of sample is not larger than 1 liter. The sample is readily taken upon opening the bottle to the atmosphere, either by opening a glass stopcock or a pinchcock on a short length of heavy-walled tubing, or by breaking off the tip of a sealed inlet orifice, being careful not to warm the bottle by contact with the hands, and then closing or sealing the orifice.

2. Samples in Partially Evacuated Bottles

Samples may be conveniently taken in partially evacuated bottles of any size up to 20 liters. A measured volume of a suitable absorbent liquid is added to a calibrated bottle and the bottle is partially evacuated by a hand pump or other means, the residual partial pressure being recorded. The bottle is opened in the atmosphere to be sampled. It should then be taken to the laboratory, or to an uncontaminated zone, shaken well, and the contents washed into a suitable container with 2 or 3 successive portions of wash solution. After this, analysis may be made by appropriate methods.

The volume of the sample is computed as follows:

$$Vs = (V - A)\frac{P_2 - P_1}{P_2}$$

where Vs = sample volume, V = volume of bottle, A = volume of absorbent added to the bottle, P_1 = residual partial pressure in the bottle, and P_2 = atmospheric pressure at the time and place of sampling.

F. SPECTROMETRY

1. Infrared

The infrared spectrometer[40] is a relatively new tool with great possibilities for use in industrial hygiene as a means of recognizing and evaluating organic materials in the air. The basis of application is that practically all organic substances possess selective absorption at certain frequencies in the infrared portion of the spectrum. The essential parts of the apparatus are a heat source emitting a continuous range of the wave lengths desired; a means of dispersing the radiation and providing narrow wave length bands at accurately known wave length positions (for this purpose prisms of sodium chloride, potassium bromide, etc. are supplied); cells for placing a suitable thickness of material for analysis in the path of the radiation; and a detector, such as a sensitive thermocouple and amplifier, for accurately measuring the radiation. Absorption cells of various thicknesses are available, from 0.05 mm. for liquids and solids to several centimeters for gases. The size, weight, and complexity of the apparatus do not make it attractive as a portable instrument; and

[38] L. B. Berger and H. H. Schrenk, *U. S. Bur. Mines Circ.* No. **7017** (1938).
[39] W. P. Yant and L. B. Berger, *U. S. Bur. Mines, Miners' Circ.*, No. **34** (1936).
[40] R. B. Barnes, U. Liddel, and V. Z. Williams, *Ind. Eng. Chem., Anal. Ed.*, **15**, 659 (1943).

the length of absorption cells would have to be considerably increased to make it suitable for measuring a few p.p.m. of most vapors in air. However, when the material to be analyzed is absorbed or dissolved in a liquid, analysis is readily accomplished, providing a liquid vehicle has been chosen that has no interfering absorption bands in the significant range for the material to be analyzed. The absorption pattern furnishes positive identification of single compounds having a known pattern; furnishes helpful clues to the composition of complex mixtures (superimposed patterns); and identifies linkages, bonds, and groups in obscure compounds. It is a quantitative tool as well, since Beer's law has been found true for this region of the spectrum (the absorption is proportional to the concentration of absorbent in the solution). Many ranges of wave lengths in the spectrum, between visible and ultra short radio waves, have yet to be explored, largely because of the difficulty of generating, controlling, dispersing, and measuring the intensity of these waves.

2. Ultraviolet

Several organic solvents, especially in the aromatic series, have characteristic absorption patterns in the ultraviolet region of the spectrum.[41] The patterns can be used to identify very small amounts of solvents, while the opacity of the solvent at specific wave lengths can be used to measure the amounts. As in the case of infrared analysis, a sample must be collected from the air by condensation, by collection on silica gel (page 208), or by scrubbing air through a tenacious nonvolatile solvent that has no interfering absorption pattern. It is frequently necessary to refrigerate the scrubber in order to obtain high collection efficiency.

3. Light Absorption

Visible light spectrometry[42] is similar to infrared and ultraviolet spectrometry except that there are fewer compounds having distinctive absorption patterns. In spectrometry accurate results require a source of radiant energy confined to a narrow band of known (calibrated and checked) wave length, recognition and consideration of interfering absorption, and reliable measurement of transmitted energy.

DUSTS, FUMES, AND SMOKES

I. Sampling

The instrument to be employed for sampling and evaluating particulate matter in the atmosphere will depend upon the availability of instruments, place to be sampled, nature of the contaminant, and purpose of the investigation.

A. IMPINGEMENT

There are several dust-sampling instruments that employ the principle of impingement. Dust carried by air at high velocity is impinged against a plate, where it is arrested by an agent such as a film of water or other liquid, gelatin, or grease.

[41] M. E. Maclean, P. J. Jencks, and S. F. Acree, *J. Research Natl. Bur. Standards*, **34**, 271 (1945).

[42] M. G. Mellon, *Ind. Eng. Chem., Anal. Ed.*, **17**, 81 (1945).

1. Greenburg-Smith Apparatus

In the United States the Greenburg-Smith[43, 44] standard impinger and its midget counterpart are the most widely used instruments for obtaining dust samples for evaluation by counting. In the standard instrument air is drawn through an impinger nozzle or orifice 2.3 mm. in diameter at the rate of 1 cu. ft. per minute and impinged against a glass plate set perpendicular to, and 5 mm. distant from, the orifice. Each orifice must be calibrated, and if necessary adjusted to this size and flow. The plate may be the bottom of the sample flask itself. The plate is covered to a depth of at least 1 in. with dust-free water or other suitable liquid, which serves to trap and retain the dust particles after they strike the plate. The device is usually equipped with an electrically driven air pump, but may be obtained for hand operation, or with an ejector utilizing compressed air as the means of aspiration.

This device is suitable for sampling all air-borne dusts greater than 0.7 μ in diameter (dust within the range of definition by light-field technique), but at the standard rate of flow its efficiency for dusts of smaller size falls off rapidly. When set up with two impinger flasks in series, however, it can be used for particles somewhat smaller in size, such as lead fumes and fluoride fumes, the greater part of which are below 0.5 μ in diameter. Of freshly formed fumes frequently the greater portion is caught in the second impinger flask. This may be due to the particles having become moistened in passing through the first flask and so being more easily trapped in the second. Another possibility is that condensation of water upon the individual particles takes place as a result of the cooling of the saturated air as it suddenly expands upon emerging from the orifice into the second flask.

With freshly generated lead fume,[45] the efficiency has been found to range from 55 to 60 per cent, 34 to 37 per cent in the second flask, while with fumes 1 to 3 hours after generation 60 to 65 per cent was collected in the first impinger and 13 to 32 per cent in the second, for a total collection efficiency of 78 to 92 per cent. With fluoride fume collected in a magnesium foundry the second impinger contained 13 to 38 per cent of the total collected (see page 218), and the collection efficiency compared with a commercial electrostatic precipitator was 94 to 120 per cent. A small and undetermined portion of the fluoride contamination was doubtless gaseous.

2. The Midget Impinger

The midget impinger is similar to the standard instrument except that it is usually hand-operated and draws a sample volume of 2.8 liters per minute through an orifice 1 mm. in diameter. Each impinger nozzle must be calibrated, as deviations in nozzle size of over 50 per cent are found. This instrument has been shown to be as satisfactory as the standard apparatus for sampling most dusts in the range of 0.7 to 10 μ, but it is not suited to the sampling of particles below 0.5 μ, such as fumes. Its

[43] L. Greenburg and G. W. Smith, *U. S. Bur. Mines Repts. Investigations*, No. **2392** (1922).

[44] C. E. Brown and H. H. Schrenk, *U. S. Bur. Mines Circ.* No. **7026** (1938).

[45] J. B. Littlefield, Florence Feicht, and H. H. Schrenk, *U. S. Bur. Mines Repts. Investigations*, No. **3401** (1938).

suitability for sampling asbestos fibers has been questioned. It can be operated by a hand crank and is therefore independent of a power supply, and is suitable for use in inflammable vapors or dusts. The entire impinger, complete with 9 flasks, is contained in a relatively light and easily portable case.

3. The Konimeter

The konimeter is a dust-sampling instrument introduced by R. M. Kotze in 1916, and later modified. In its present form (Zeiss Konimeter) it consists essentially of a small valveless spring-operated piston pump and a circular plate for impingement of the dust. When the piston is depressed it is held against the compression of the operating spring by a catch. Releasing the catch allows the piston to move rapidly to a stop and creates at the discretion of the operator a 2.5-ml. or a 5-ml. void, pulling atmospheric air through a round 0.5- to 0.6-mm. orifice and impinging it against a circular glass plate held 0.5 to 0.6 mm. distant from and perpendicular to the impinging orifice. The circular plate, held in a metal rim, is covered with an adhesive film to retain the dust particles, and has 30 numbered, equally spaced sample positions.

For use, the glass disk is cleaned, coated with an adhesive (glycerine jelly is recommended by the United States Bureau of Mines[46]), examined under a microscope, and, if satisfactory, inserted in the konimeter or a spare carrying case. Usually several samples are taken in the same work area in order to estimate average conditions. The instrument is not satisfactory for high dust concentrations: even a 2.5-ml. sample of visibly dusty air is likely to be too much to count. For very low dust concentrations more than one 5-ml. sample may be taken at the same position of the disk. In the technique used by the United States Bureau of Mines, the samples are estimated by counting sectors of the spots under a microscope with 200 magnification, using light-field illumination. The counts cannot be directly compared to impinger counts, but are useful in estimating the effectiveness of dust-control methods, and for comparing dustiness in a situation where the type of dust remains more or less constant but its concentration varies with numerous conditions. The dust is counted without prior treatment. Ease and speed of sampling and counting are the chief advantages of the method. Techniques used in countries other than the United States vary from that described, but will not be elaborated upon here.

4. Owen's Jet

The Owen's jet sampling device draws an air sample of 50 ml. or more through a moistening chamber and then at high velocity through a narrow slot, usually 1 cm. long and 0.1 mm. wide. The resulting lowered temperature from greatly reduced pressure on the air passing through the slot causes condensation of moisture on any dust particles and the droplets are impinged against a cover glass where they adhere and later dry, leaving the dust on the cover glass. The ribbon of dust thus formed is

[46] J. B. Littlefield, C. E. Brown, and H. H. Schrenk, *U. S. Bur. Mines Circ.* No. 6993 (1938).

not uniform and is therefore difficult to count. It has all the disadvantages of the konimeter and is, further, susceptible to different efficiencies depending upon the rate of pull on the pump plunger. The instrument has a value for comparisons, as does the konimeter. The Bausch and Lomb dust counter is a modification of this device.

B. ELECTROSTATIC PRECIPITATION

The electrostatic precipitator has a high efficiency for collecting all types of particulate matter. This device utilizes the principle of the Cottrell precipitator whereby air is drawn through a tube within which is a central conductor wire electrode, the other electrode being formed by the tube or its conductor lining or covering. For the purpose of air sampling the tube diameter is usually between 1½ and 3 in. and the voltage used ranges from 8000 to 30,000. The relationship of tube diameter, air flow, and voltage must be within certain limits in order to approach its maximum efficiency of 100 per cent. A commercially available portable outfit similar to one described by Barnes and Penney[47] operates on a 110-volt 60-cycle current producing under favorable circumstances a secondary voltage of 8000 to 15,000. It is important that this voltage be checked, and maintained at not less than 10,000. The precipitator is equipped with a fan and a flowmeter calibrated to draw approximately 3 cu. ft. of air per minute. This volume, likewise, should be checked by a suitable meter. The dust content of the air is deposited upon the inside of the precipitator tube or, in some instances, on the inner electrode. Any deposit should be carefully preserved and transported to a laboratory for weighing, counting, or chemical analysis. This device is especially useful for sampling fumes, smokes, or other suspended matter with a particle size below ¾ μ in diameter, in which range the impinger apparatus is not satisfactorily efficient. It is not suitable for use in inflammable atmospheres.

As a comparison of efficiency between the standard impinger and the electrostatic precipitator for sampling fluoride fumes in a magnesium foundry, the following figures are of interest. With two impingers in series, from 62 to 87 per cent of the total amount collected was found in the first impinger and from 13 to 38 per cent in the second. On the average there was 74 per cent in the first and 26 per cent in the second. Samples collected simultaneously with a commercial electric precipitator (10,000 volts by spark-gap calibration) at the same location yielded from 80 to 106 per cent of the amount of fluorides found in the two impingers, the average being 90 per cent. The results indicate that the two impingers in series were 10 per cent more efficient than the precipitator for fluoride fume. No attempt was made to determine what percentage of the fluorides existed in the gaseous phase, but, inasmuch as some of the fluoride was disseminated into the air by contact of ammonium bifluoride with hot sand molds and molten magnesium, it is reasonable to suppose that some of the fluoride existed as hydrogen fluoride gas. This gas, of course, would not be caught by the precipitator, but some would be caught by the impingers, thus

[47] E. C. Barnes and J. W. Penney, *J. Ind. Hyg. Toxicol.*, **20**, 259 (1938).

increasing their efficiency ratio and indicating a falsely high collection efficiency, when compared with that of the precipitator.

This precipitator has been found satisfactory for collecting silica dust samples for quantification by counting.[48] Another electrostatic collector for dusts for light-field counting techniques was devised by Barnes.[49] This device consists of an aluminum cylinder 9 in. in diameter and 12 in. long holding about ½ cu. ft. of air. The ends can be closed with micarta disks that support an ionizing wire axially through the center of the cylinder. A slide adapter in the side of the cylinder holds a special microscope slide with conducting surface. In use, the cylinder is opened and moved to the sample location, the ends are closed, the slide is uncovered, and the dust is deposited electrostatically in about 15 seconds. Several samples can be taken on the same slide if desired. It has been stated that the device is nearly 100 per cent efficient and that the slide receives a uniformly distributed, proportionate share of the dust in the air in the cylinder at the time the current is turned on.

C. FILTRATION

Paper thimbles[50] have been used successfully for collecting various dusts, including explosives. They have a very high efficiency and at 2 cu. ft. per minute air flow have been found to collect nearly 100 per cent of most dusts and around 50 per cent of tobacco smoke. Filters made of salicylic acid,[51] sugar, or other material to be dissolved later in a liquid medium leaving the dust in suspension, have also been used. Filter-paper disks have been used for sampling: the blackening of the paper, after a measured volume of air has been drawn through, may be compared with standards; or the samples obtained may be used for counting, with results comparable to results obtained by the impinger method.[52] Large filter-paper[53] cups, with inverted cones, have been used for rapid sampling of particulate matter from large air volumes.

D. THERMAL PRECIPITATION

Green and Watson[54] devised a thermal precipitator that draws air by water displacement at about 7 ml. per minute through a 0.051×0.95 cm. slot. A nichrome wire 0.025 cm. in diameter, heated to 100° C., is held centrally in the slot and the walls of the slot are cover slips backed by brass blocks for cooling. As the air passes between the hot wire and the cool surface of the cover glass any suspended dust particles are deposited upon the cover slips. The efficiency of the device is said to be 100 per cent. The deposit is suitable for microscopic examination. One technique includes counts and particle-size determinations with the electron microscope.[54a]

[48] H. H. Schrenk, *Am. J. Pub. Health*, **30**, 1183 (1940).
[49] E. C. Barnes, *Am. J. Pub. Health*, **26**, 274 (1936).
[50] L. T. Trostel and H. W. Frevert, *Ind. Eng. Chem.*, **15**, 232 (1923).
[51] F. R. Holden, W. C. L. Hemeon and E. C. Hyatt, *Seventh Annual Meeting Amer. Ind. Hyg. Assoc.*, Chicago (1946).
[52] C. E. Brown, *U. S. Bur. Mines Repts. Investigations* No. **3788** (1944).
[53] L. Silverman and C. R. Williams, *J. Ind. Hyg. Toxicol.*, **28**, 21 (1946).
[54] H. L. Green and H. H. Watson, *Medical Research Council, Special Reprint* No. **199**, London (1935).
[54a] J. H. L. Watson, *Can. J. Research*, **21**, 89 (1943).

E. SEDIMENTATION

The sedimentation cell, as devised by Green,[55] is a brass cylinder 6 cm. deep and 3.6 cm. in diameter closed at the top with a swivel lid and at the bottom by a brass slide mounting two ½-in. cover slips. The cylinder is filled with atmosphere and then closed at the point where the sample is desired, and left to stand 1 to 3 hours. Then the cover slips are removed and examined under a microscope with high resolving power. The method is suitable for determining the count and particle size of dusts down to 0.2 μ in diameter (3 hours settling time). The sedimentation cell is intended as a laboratory or research instrument and not for field use.

II. Evaluation of Dust Samples

The evaluation of a dust sample may be made on a weight basis, with or without the aid of chemical analyses, or it may be accomplished for all insoluble pneumoconioses-producing and nuisance dusts by determining the number of particles in a measured volume of air.

After dust particles from a known volume of air are collected, an aliquot portion must be counted in order to compute the number of particles suspended in a cubic foot of the atmosphere sampled, the cubic foot being the accepted unit for comparison in the United States.

A. MAKING A DUST COUNT

1. Counting Impinger Samples

Dilution of sample. Impinger samples are diluted, either in the impinger flask or in a volumetric flask, with dust-free distilled water or other sampling medium to a definite volume, which will depend upon the size of the sample, the dust concentration, and the method of counting to be employed.

Counts of 20 to 75 per fourth of the ruled field of the Whipple disk are held to be most satisfactory; though, with a carefully prepared dust-free sampling medium, properly cleaned cells, and careful handling of samples and controls, it is practical to make counts of less than 20 per quarter field. If necessary, the sampling media should be redistilled in glass until counts of not more than 3 or possibly 4 per quarter field are obtained. Samples giving counts of over 100 per quarter field usually warrant dilution. If the microprojector is to be used, counts of 5 to 250 particles per 0.05 cu. mm. are practical; for cells of 1-mm. depth, a 10 cm. $\times$ 50 cm. strip of screen at 1000x magnification is the equivalent of 0.05 cu. mm.

Choice of counting chamber and method of cleaning. There have been many heated condemnations and defenses of special types of counting chambers. The majority of persons prefer those of 1-mm. depth, but individual tastes differ and much outstanding work has been done using cells of 0.1- and 0.25-mm. depth. Where liquids other than water are to be used, fused cells are more satisfactory than cemented cells. One objection to the Sedgwick-Rafter cell, that of the difficulty of

[55] H. L. Green, *J. Ind. Hyg. Toxicol.*, **16**, 29 (1934).

cleaning, is easily overcome by the use of a good aqueous soap solution to which meta- and pyrophosphates have been added. (Either "Calgon" and soap solution, or "Calgonite," is a very satisfactory cleaning agent of this type for counting chambers.) After the cells are cleaned they should be rinsed with dust-free distilled water, followed by alcohol, if desired. They are then drained and wiped dry with lens paper or a clean, lint-free cloth (preferably linen, though some analysts use other materials, such as silk). In some laboratories, the drained cells are dried in an oven. A camel's-hair brush has been recommended for brushing out cells after drying, but the success of this procedure is open to question. Some persons allow counting cells to stand in a covered container of clean alcohol until wanted for use, while others prefer to dry them and keep them wrapped in lens paper or cloth. If the cleaning routine is carried out just prior to the use of the cells, the possibility of contamination with dust is lessened.

The majority of our standards have been based upon impinger samples collected in water, and counts made in cells 1 mm. deep after 20 minutes settling time. For most inorganic dusts the count in 1-mm. cells increases with settling time rather rapidly during the first 20 to 30 minutes and more gradually, but consistently, for hours thereafter. The increase in count during the first 20 minutes is so rapid as to make results taken during this period of little value. Except for the fact that 20 minutes has been the accepted settling time, counts made after 30 to 45 minutes settling would be more comparable, because the rate of increase is less than at 20 minutes. When using propyl, isopropyl, or butyl alcohol as the collecting medium, 30 minutes settling time is thought to be comparable to 20 minutes with water. Cells of less than 1-mm. depth give higher results with similar settling time or the same results with shorter settling time. When the dusts have a density of less than, or even approaching, that of the collecting liquid it is impossible to count all particles in any cell without racking from top to bottom.

Filling the cell and preparation for counting. The dust suspension is agitated and a sample sufficient to fill the counting cell is transferred, usually by pipette, into a clean Sedgwick-Rafter cell, Dunn cell, or other suitable counting chamber of accurately controlled depth, which may be from 0.1 to 1.0 mm. (It is evident that an error in cell depth of 0.1 mm. on a 1-mm. cell introduces an error of 10 per cent. Many of the cells supplied by manufacturers have been proved by measurement to be 10 to 40 per cent oversize.) It is neither necessary nor desirable to filter the suspension through a 325-mesh screen as was formerly the recommended practice. If leakage or evaporation is found to occur when alcohol is the sampling medium and the Dunn cell is used for counting, a thin film of dust-free liquid petrolatum between the glass surfaces will prevent the difficulty.

FIG. 5. Sedgwick-Rafter cell.

Microscopic arrangement for light-field counting. For light-field counting, our present accepted standard, the amount of light used should be adjusted to prevent glare, but actual

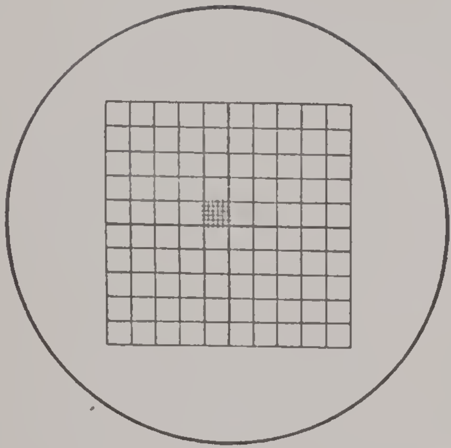


FIG. 6. Ruling of Whipple ocular micrometer disk.

shading, tilting of the mirror, and the use of spotted cells or blue filters must be tempered with caution, else a grossly erroneous count lying between the true light-field and dark-field counts may be obtained. The usual microscopic arrangement includes a 16-mm. objective and a 7.5x ocular containing a Whipple disk, the tube length being adjusted so that the Whipple disk exactly subtends 1 sq. mm. of the floor of the counting cell. This adjustment is made by the use of a stage micrometer.

Method of making and computing counts. The recommended practice for counting is to prepare two cells from each dust sample and to count one fourth of the ruled field of the Whipple disk in five well-separated representative locations of each cell. The ten counts are averaged and from this is subtracted a similarly obtained count of a control sample of the collecting liquid through which no air has been drawn. The control count compensates for dust acquired in manipulation, as well as dust in the sampling medium or the microscopic system. This average net count per fourth of the field is then computed to million particles per cubic foot in the sampled atmosphere, taking into account air volume sampled and volume of impinger liquid.

$$\text{Particles per cu. ft.} = \frac{\text{count per fourth of field} \times 4 \times 1000 \times \text{ml. of sample liquid}}{\text{cu. ft. of air sampled}}$$

There is considerable variation in the manner of making dilutions and filling cells, in the length of settling time, the choice of a counting cell, and the microscopic system employed; therefore to expect greater correlation than $\pm$ 10 per cent between two independent counts is to be overly optimistic, and variations of over 50 per cent are not uncommon. Despite all of these objections our present system of evaluation is not to be condemned, but we should encourage research into better methods and be mindful of the folly of evaluations based upon a single dust count. We should avoid the idea that the threshold limits of dustiness now accepted are absolute figures rigidly separating safe atmospheres from dangerous ones. Rather, they should be regarded as bench marks of desirable control.

Dark-field versus light-field counting. Dark-field illumination obtained by means of a Zeiss "Dissecting Condenser," and counts made with a microscopic system employing a 16-mm. achromatic objective with N.A. = 0.2 (8x), a 30x ocular, and a tube length adjusted to give a magnification of 250x have been shown to yield results from 2 times to more than 50 times as high as those obtained by standard light-field technique.[56] The limit of visibility of this arrangement is about 0.1 μ. The

[56] T. Hatch and C. L. Pool, *J. Ind. Hyg. Toxicol.*, **16**, 177 (1934).

ratio of DF count to LF count increases with an increasing proportion of particles less than 0.7 μ in diameter and is an indication of particle size. This does not necessarily indicate that the dark-field count is a better index, or even that it would be after the establishment of sufficient correlation between lung damage and dustiness determined by such dark-field counts. Although impinger samples are more easily counted by the dark-field technique, and with much higher results, the collection efficiency of the impinger as now used drops so rapidly with diminishing particle size, for particles below ¾ μ, that the advantage in counting may be more than offset by decreasing efficiency of collection. Our present method of evaluation is largely limited to those particles above 0.7 μ in diameter: whether this gives rise to serious errors remains to be proved. It has been suggested that particle size may be a factor in explaining the relatively low light-field counts found in the silica brick industry in work atmospheres where silicosis is known to occur. It would seem desirable to collect samples in this and some other silica exposures and, after evaluation of all particles in the range between 0.1 and 5.0 μ, make a statistical study in an effort to illuminate the effect of the smaller particles as well as possibly to explain the incidence of silicosis in silica brick manufacture.[57]

The microprojector. The microprojector[58] furnishes a useful variation in counting methods for evaluating impinger samples, whereby the dust image is projected, usually at a magnification of 1000 diameters, onto a ruled screen. A 16-mm. objective is used and the increased magnification is obtained by employing higher power in the ocular and by projection. Two cells are prepared and each is counted by counting all the particles in five well-separated representative fields of 0.05 cu. mm. each (10 cm. × 50 cm. strip on the screen, at 1000x). A similar count of the control is then subtracted from the average of the counts on the two sample cells, and the final computation is as follows:

$$\text{particles per cu. ft. of air} = \frac{\text{count in 0.25 cu. mm.} \times 4 \times 1000 \times \text{ml. of dust suspension}}{\text{cu. ft. of air sampled}}$$

The microprojector can be used for both counts and particle-size determinations, does not cause excessive eye strain, and, at least among the inexperienced, tends to promote closer agreement and reproducibility of counts. It is probably not a time saver when counts are being made by one individual. With direct counting through a microscope, the analyst can arrange all his material within arm's length and not spend time opening and closing the viewing booth door and walking from booth to microscope to adjust the light source and to fill cells and place them on the stage. The time gained with the microprojector in avoiding secondary dilution of some samples does not compensate for this loss. The microprojector is, however, very useful for counting as well as for particle size determination, yields dependable and reproducible results, and is an interesting and valuable demonstration piece. The

[57] W. B. Fulton, F. E. Butters, A. E. Dooley, F. B. Koppenhaver, J. L. Matthes, and R. M. Kirk, *A Study of Silicosis in the Silica Brick Industry.* Bur. of Ind. Hyg., Dept. of Health, Harrisburg, Pa. (1941).

[58] C. E. Brown, L. A. Baum, W. P. Yant, and H. H. Schrenk, *U. S. Bur. Mines Repts. Investigations* No. **3373** (1938).

midget counterpart[59] requires less space and obviates the necessity for remote controls to manipulate focusing and mechanical-stage controls.

2. Counting Konimeter Samples

Konimeter samples may be examined and counted by use of the special microscope attached to some konimeters. More satisfactory counts are obtained by using a regular microscope with light-field illumination and fitted with a special holder so that the konimeter dust spots can be rotated and any one can be brought into view readily. A satisfactory magnification has been found to be 200x obtained by using a 10x objective with a compensated 20x ocular. The ocular is fitted with a squared micrometer scale, similar to that shown in Figure 7, with two crossed lines that outline sectors of 18 degrees. The parallel lines *ai* and *id* are for use in estimating the size of particles. In counting, the scale is centered over the dust spot and all the particles in the two 18-degree sectors are counted, giving a total count of all the dust in 36 degrees or 10 per cent of the entire spot. From this count must be subtracted a control count of an equal area of the unused plate and adhesive film. The net count of 10 per cent of the total area of the dust spot is multiplied by 10 and divided by the volume of air sampled (in milliliters) to obtain the number of particles per milliliter. If the results are desired in million particles per cubic foot, the number of particles per milliliter may be multiplied by 0.02832; for a 2.5 ml. sample the actual count for a 36-degree sector may be multiplied by 0.113; and for a 5-ml. sample, the 36-degree sector count should be multiplied by 0.057.

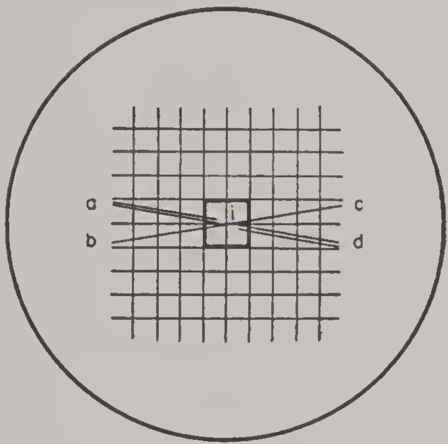


FIG. 7. Micrometer scale for counting konimeter samples.

3. Counting Owen's Jet Samples

The cover slip with dust deposit is mounted dry with dust side down on a microscope slide and examined under a microscope with an oil immersion objective, dark-field illumination, and about 1000x magnification. An ocular with a crossbar ruled micrometer with 1-mm. squares is used; a representative band of one square width across the ribbon of dust is selected, and all the particles in this band are counted. Two or more bands may be counted and averaged if desired, but the effort is hardly justifiable because the ribbon is rarely uniform in distribution or width throughout its length, especially at each end. The number of bands in the length of sample ribbon must then be determined if this factor has not previously been established. Lower magnification must be used to measure the ribbon in terms of the ruled ocular disk and the relation between objectives, if not known, can be established by the use of a stage micrometer. Since the volume of air sampled was 50 ml.,

[59] C. E. Brown, *U. S. Bur. Mines Repts. Investigations* No. 3780 (1944).

the number of particles per milliliter is computed by multiplying the number found in one band by the number of bands and dividing by 50. This result may easily be computed to million particles per cubic foot by multiplying it by 0.028, but no correlation with standard impinger results should be assumed from such computation.

B. DETERMINING PARTICLE-SIZE DISTRIBUTION

Use of the microprojector[60, 61] is perhaps the most satisfactory method of determining the particle-size distribution of dust samples collected either by the impinger (one or more drops evaporated to dryness on a slide), the konimeter, the Owen's jet, or the electric precipitator. While a magnification of 1000 diameters (employing $10x$ objective) is ordinarily used for counting, a magnification of 10,000 diameters ($90x$ oil-immersion objective) is recommended for determining the particle size, a change in tube length being necessary to adjust the magnification. Particle-size distribution is determined by estimating the size of each of the particles in representative fields of the sample using the 0.5-μ squares on the screen for comparison. The particles are classified according to diameter in intervals of each 0.5 μ, counts for each class being registered on a Marbel blood counter, or by other suitable means. The number of particles of a particular size that occur in a given count determines that size frequency. These frequencies are usually expressed in percentages of the total count.

The data from a particle-size determination may be presented graphically, as in Figure 8, by plotting the counts as ordinates against the sizes as abscissas at regu-

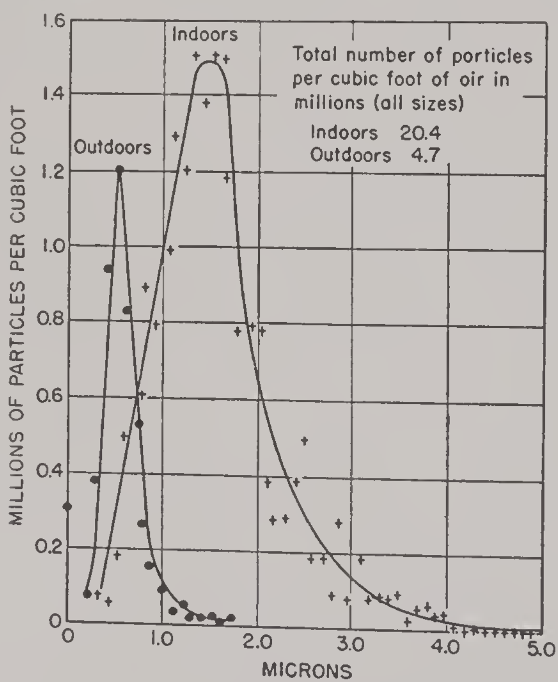


FIG. 8. Graphic illustration of size distribution of indoor and outdoor dust at granite cutting plants.

[60] C. E. Brown and W. P. Yant, *U. S. Bur. Mines Repts. Investigations* No. **3289** (1935).
[61] C. E. Brown, L. A. Baum, W. P. Yant and H. H. Schrenk, *U. S. Bur. Mines Repts. Investigations* No. **3373** (1938).

larly spaced size intervals. This graph clearly illustrates the size variation and counts, and shows two typical frequency distributions.

When particle-size data are tabulated, as in Table 4, which has size groups at 0.5-μ intervals and frequencies in percentage, it is again possible to compare the characteristics of different dust dispersions. The median is the cumulative 50 per cent size, usually a representative measure of average dust size. It should be noted,

TABLE 4

Size-Frequency Distribution of Various Industrial Dusts as Compared to Outdoor Dust[61a]

Kind of dust	Number of samples	Median	Average frequency in per cent (size group in microns)											
			0 to 0.49	0.5 to 0.99	1.0 to 1.49	1.5 to 1.99	2.0 to 2.49	2.5 to 2.99	3.0 to 3.49	3.5 to 3.99	4.0 to 4.49	4.5 to 4.99	5.0 to 5.49	5.5 to 5.99
Outdoor dust	179	0.5	56.0	41.0	2.5	0.5	....	....	....	....	....	....	....	....
Sandblasting	9	1.4	1.4	19.7	34.7	20.3	12.6	5.2	2.8	1.6	1.1	0.2	0.2	0.2
Granite cutting	4	1.4	2.0	19.0	33.6	24.5	10.4	4.6	3.1	0.6	0.9	0.3	1.0	....
Trap rock milling:														
Crusher house	1	1.4	0	13.0	39.0	33.0	10.5	2.5	2.0	....	....	....	....	....
Screen house	1	1.3	2.0	31.5	33.0	16.0	10.0	4.5	2.5	0.5	....	....	....	....
Disk crusher	1	0.9	10.0	48.0	31.0	6.0	3.0	1.0	1.0	....	....	....	....	....
Foundry parting compound	2	1.4	0.5	22.0	42.0	17.3	9.2	5.0	1.5	2.0	0.5	....	....	....
General foundry air	1	1.2	0	26.0	48.0	17.0	8.0	1.0	....	....	....	....	....	....
Talc milling	1	1.5	0	16.0	32.0	20.0	13.0	7.0	5.0	2.0	2.0	2.0	0	1.0
Slate milling	1	1.7	1.0	13.0	29.0	17.0	14.0	14.0	6.0	4.0	1.0	0	1.0	....
Marble cutting	1	1.5	0	12.0	37.0	21.0	10.0	11.0	3.0	0	1.0	2.0	2.0	1.0
Soapstone dust	2	2.4	1.2	16.0	19.0	13.0	11.0	6.0	6.5	4.5	5.5	3.3	2.5	11.5
Aluminum dust	1	2.2	3.0	8.0	20.5	14.0	11.5	9.0	6.5	3.0	3.5	4.0	7.0	10.0
Bronze dust	1	1.5	1.0	12.0	33.5	25.0	21.0	6.0	1.5	....	....	....	....	....

however, that in the case of some dusts with wide variations in size the mode may prove not to coincide with the median, and would be a better measure of central tendency: aluminum dust, soapstone dust, and slate milling, in all of which the mode, value of most frequent occurrence, is 1.25 μ, although the medians range from 1.7 to 2.4 μ and in each case represent much smaller frequencies than the modal ones.

Still another method of treating the data is to plot the cumulative percentage of particles for the different class intervals, percentage less than a stated size, against the size on logarithmic probability paper[62] and draw the best straight line through the points. From this line, which assumes a normal probability distribution, the geometric mean[63] is observed as the 50 per cent size and the standard geometric deviation readily computed by dividing the 84.13 per cent size by the 50 per cent size. As an example of this treatment, the screen-house sample from a traprock mill has been taken from Table 4 and plotted on logarithmic probability paper and the parameters determined in Figure 9.

Results similar to those given by the microprojector are obtained by the use of

[61a] J. J. Bloomfield, *U. S. Pub. Health Repts.*, **48**, 961 (1933).

[62] P. Drinker, *J. Ind. Hyg.*, **7**, 305 (1925).

[63] P. Drinker and T. Hatch, *Industrial Dust*. McGraw-Hill, New York, 1936.

the filar micrometer eyepiece at a magnification of 1000 diameters, but in this instance several representative fields are chosen and the diameters of the first 200 particles encountered in each are measured by moving the cross hair across the field from left to right.

A particle-size estimation of dusts can be made by the use of a photomicrograph, which has the advantage of being a permanent visual record.

In any of these methods the results are only relative. The optical systems employed fail to resolve particles appreciably smaller than 0.5 μ and, since it has been demonstrated that dusts have widely varying proportions of particles below this

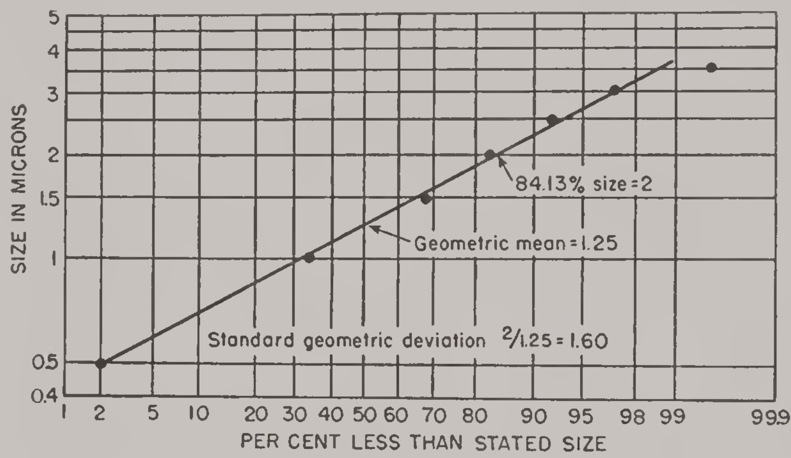


FIG. 9. Logarithmic probability plot of data on screen house taken from Table 4.

size, it is evident that the absolute average particle size is necessarily less than the determined value. Since the significant size range of dusts injurious to health is now believed to be below 3 μ, with an as yet undetermined lower limit of significant size, this factor of unresolved particles may be of considerable importance.

Holden and Hyatt[64] propose that, in the evaluation of exposures to dusts containing free silica, a sufficiently large sample of air-borne dust be collected and sized by allowing the suspension in alcohol to settle for a measured time. The larger particles settle out leaving in suspension the particles 5 μ or less in diameter; the silica content of this latter fraction is determined in order to appraise the relevant silica dust exposure.

C. WEIGHING THE SAMPLE

It is possible to evaluate certain classes of particulate samples by weight. This may be true of impinger samples (especially useful with soluble dusts) as well as samples collected by filtration or by electrostatic precipitation. In this manner the milligrams of toxic contaminants per cubic meter of air may be determined, and by

[64] F. R. Holden and E. C. Hyatt, *Annual Meeting Ind. Hyg. Foundation*, Pittsburgh (1945).

ignition the sample may be divided into combustible and incombustible matter. Bloomfield and DallaValle,[65] by weighing 611 impinger samples upon which counts had been made, found a certain amount of correlation between the weight and count, as given in Table 5. Since particle-size distribution is a tremendous factor to be considered in any attempt to evaluate weight or count in terms of the other, in most cases such a conversion is not practical, and if attempted is apt to be translated into erroneous conclusions.

TABLE 5

Correlation between Particle Counts and Weights of Air-Borne Industrial Dusts

Kind of dust	Coefficient of correlation	Millions of dust particles equivalent to 1 mg.
Bituminous coal	0.847	31
Anthracite coal	0.771	44
Granite	0.755	31
Metal grinding and polishing	0.698	19
Cement	0.694	15
All dusts	0.726	35

D. ANALYZING THE DUST

1. *Chemical Analysis for Toxic Materials*

Dusts collected by the impinger, the paper thimble or other filtration medium, or the electric precipitator may be analyzed by chemical methods, due consideration being given to the amount of sample in relation to the sensitivity and precision of the method. Methods of analysis for the toxic elements, metals and nonmetals, will be discussed individually in Volume II of this book. Differentiation of free silica (SiO_2) from silicates cannot be accomplished satisfactorily by chemical means. However, the quartz content of dusts containing representative particles 10 μ or more in diameter may be satisfactorily determined in samples greater than 0.1 g. by combining chemical and petrographic techniques. For such samples to be truly representative of an exposure they should be collected in the breathing zone of the workman. Nevertheless, ledge or rafter samples are not to be entirely scorned, and when selected with due consideration to obtaining air-borne rather than projected or sifted deposits they offer useful information regarding exposures, frequently more reliable than the analysis of unselected deposits or unprocessed material.

2. *Determination of Quartz*

By combined chemical and petrographic analysis. If one is interested only in the determination of free silica, especially quartz, in a sample of dust ranging in size to 10 μ or greater, it is only necessary to clean the dust, removing as much as possible of particles other than free silica, and to estimate the free silica in the residue by the use of petrographic methods. The procedure may be simplified and standardized as

[65] J. J. Bloomfield and J. M. DallaValle, *U. S. Pub. Health Bull.* No. 217 (1935).

follows. A portion of the dust, between 0.1000 and 0.5000 g., is weighed. If considerable organic matter is present the weighed sample should first be ignited, otherwise it is placed directly in a pyrex beaker and 30 ml. of concentrated hydrochloric acid plus 10 ml. of concentrated nitric acid are added. The contents of the beaker are heated to boiling on a hot plate for 20 minutes, diluted with about 200 ml. of hot water, heated to boiling, filtered through #42 Whatman filter paper, and washed with hot water. The paper and residue are then transferred to a weighed crucible, dried, ignited at about 600° C. until the carbon has disappeared, cooled, and weighed. To examine the residue with a petrographic microscope, a few particles are transferred to a microscope slide by means of a dissecting needle, a drop of immersion oil of n_D 1.545 is placed on the specimen, and it is covered with a cover slip.

A series of immersion oils may be prepared covering the refractive index range of 1.46 to 1.62 by mixing light refined paraffin oil (1.46) with monochloronaphthalene (1.62). Similarly monobromonaphthalene (1.65) may be used. If the refractive index of each constituent oil is multiplied by the percentage of that oil present, and those products are added, the sum will be approximately the refractive index of the mixture. The oils should be thoroughly mixed and the refractive index at 25° C. determined by means of an Abbe refractometer.

The specimen is examined at about 450*x* magnification: a 45*x* objective and 10*x* cross-hair ocular have proved very satisfactory. Should the particles be large enough to be identified as quartz, diatomaceous earth, chalcedony, cristobalite, or other form of free silica, or an easily estimated mixture of these with other material, the calculation may be completed by counting or estimating particles in representative fields. A 14.3*x* objective is very useful for such estimation. If the mixture contains, or is suspected of containing, feldspars (silicates) or other minerals readily confused with quartz, it is necessary to purify it further. To accomplish this, about 10 ml. of hydrofluosilicic or fluoboric acid is poured on the sample in a small platinum crucible and it is set aside for 3 to 6 days, being stirred at least twice each day with a platinum loop. At the end of the 3 to 6 days, depending upon the gross appearance of the residue, the remaining dust is filtered off, washed, dried, ignited, and weighed. It is again inspected under the petrographic microscope in order to determine the nature and purity of the residue, which should now be quartz or possibly other forms of free silica, such as chalcedony, tripoli, cristobalite, and tridymite, which dissolve in the above acids slowly, or one of a few other minerals such as silicon carbide, which is not removed by these combined acid treatments but is readily distinguishable. The petrographic identification of minerals is far beyond the scope of this chapter but a simple procedure for the identification of the quartz content of dusts, utilizing petrographic technique, may be stated as follows.

Place a minute amount (few particles) of the dust residue on a microscope slide, add a drop of immersion oil of refractive index 1.545, and cover, with a cover slip. Observe with a petrographic microscope using crossed Nicols under about 450*x* magnification. If quartz is present the small particles will appear as milky white irregular shapes. To determine whether an individual particle is quartz, use the crossed Nicols, rotate the stage, and observe that quartz particles (except when oriented with optic axis vertical) disappear four times per complete revolution of the stage. This characteristic establishes that quartz particles are anisotropic as distinguished from isotropic

crystals, which are invisible when viewed with crossed Nicols. Bring the stage to rest with a particle extinguished, then slide the analyzer Nicol prism out of the system, focus on the edges of the crystal, and raise the microscope tube from focus. A light halo surrounding the particle will move into or away from the crystal depending upon its orientation, because this halo (Becke line) always moves toward the medium of higher refractive index when the microscope tube is raised from focus. Now turn the stage exactly 90 degrees in either direction and repeat this procedure. If the particle is quartz the halo of light will move in the opposite direction. This is true because quartz has two indices of refraction, 1.544 and 1.553, both close to, and one on each side of, 1.545, the refractive index of the immersion oil. The refractive index of a submerged crystal may be judged to be very near that of the immersion oil if there is a lack of clear distinction of boundary lines; this occurs when the difference in refractive indices is less than 0.01. When the difference is less than 0.001 a submerged crystal can be seen only with difficulty. If the particle under examination fits these characteristics, that is, irregular shaped, milky white between crossed Nicols, two refractive indices one just above and one barely below 1.545, it may be suspected of being quartz. It is good practice to check a sample now with oil of n_D 1.57 to make certain that the crystals have both indices less than 1.57.

The identity of the crystals may be verified by further scrutiny. Center a particle exactly under the cross hairs and align the microscope system so that the particle does not move from position during a complete revolution of the stage. Now, by means of a Wright's diaphragm—or less satisfactorily with the Bertrand lens, if the microscope is so equipped, and no Wright's diaphragm is available—isolate this crystal and observe its interference figure.[66] This test cannot be applied successfully to particles appreciably smaller than 10 μ in diameter. It is done with crossed Nicols and upper lens condenser (converger) swung into place. Upon rotation of the stage a black cross on a light field, or portions of the arms of a cross, can be seen (interference figure for uniaxial crystal). If only portions of the arms making up the cross are visible, the analyst must imagine the complete figure in order to choose the section he wishes to investigate (see Fig. 10).

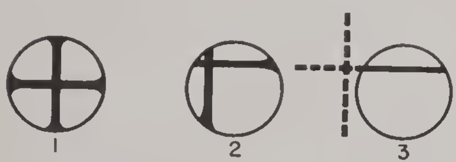


Fig. 10. Interference figures of uniaxial crystals (quartz).

A crystal is rarely found oriented so that the cross is in the center of the field, as in 1 (optic axis figure); infrequently, with the axis of the cross visible at or near the circumference of the field, as in 2; but usually, as in 3, where only the arms of the cross, appearing as straight or very slightly curved bars extending perpendicular to the observer, move straight across the field from left to right, or vice versa, or extending horizontal, move from top to bottom, or vice versa. The crystal may now be further classified as positive or negative by the use of a quartz wedge, mica plate, or selenite plate. First choose the lower right quadrant, if only the arms (bars) are visible, by rotating the stage until a horizontal bar has passed across the field away from the observer and a perpendicular bar is just out of view to the left. Now, as a quartz wedge is inserted into its slot as a bisector of this field, color curves will move outward if the particle is quartz (positive). With a mica plate so inserted, a black dot will appear in this and in the upper left quadrant, while with a selenite plate these same areas (3 to 6, and 9 to 12 o'clock, respectively) will have a yellow tinge and the other 2 quadrants will appear blue. With negative crystals opposite results are obtained. The particle that has met these requirements may now be definitely identified as quartz because it has been found to be anisotropic, uniaxial, positive, with indices of refraction of barely less than 1.545 (1.544) and between 1.545 and 1.57 (1.553). No other crystalline material fits all of these characteristics.

If the sample on first observation is found to contain a large percentage of particles other than quartz (feldspars and other silicates), it is then necessary to treat with hydrofluosilicic acid. After treatment the residue is again examined and if found to be quartz a correction of 0.7 per cent

[66] E. E. Wahlstrom, *Optical Crystallography.* Wiley, New York, 1943.

per day should be added to the quartz residue to compensate for its slight solubility in hydrofluosilicic acid.

Other forms of free silica as well as all other minerals may be similarly identified by the petrographic microscope. Anyone interested in this method of identification should obtain samples[67] of each mineral he wishes to be able to identify, pulverize some of each in a diamond mortar, and practice with known pure materials until all of these characteristics are readily recognized. With the aid of samples and a table for the determination of minerals,[68] along with a few good texts,[69-73] the field may be broadened to include many minerals.

Impinger samples ordinarily do not have a sufficient number of particles 10 μ in diameter or larger upon which an interference figure can be obtained, and therefore any petrographic method applied to them must depend largely, if not entirely, upon refractive indices. Such methods[74, 75] do not differentiate between quartz and other minerals of the same or similar refractive index, such as the feldspars, mica, talc, and some other minerals frequently found associated with quartz. They are intended to be rough estimates only, and give a maximum value rather than a true quartz value. However, in many situations a knowledge of the composition of the minerals from which the dust was generated can be used advantageously, and can give the maximum estimate the status of a true value by ruling out any interfering minerals in the same refractive index range that are known to be not present.

By x-ray diffraction. Where all of the dust particles are less than 5 μ in diameter, the only successful means so far devised of determining the crystalline, free silica content is by means of x-ray diffraction. When x-rays strike an object some of the rays are diffracted. If the x-rays are monochromatic and a beam of parallel rays is directed at a finely powdered pure material this diffraction assumes a characteristic and reproducible pattern that can be registered as lines on a photographic film (Fig. 11). The rays that pass directly through the powdered substance provide a reference mark. This same material, whether in its pure state or mixed with other matter, will reproduce the same pattern even though many other lines may be produced by other constituents in the mixture. The pattern then serves as a reliable identification, which is thought to depend upon crystalline structure.[76] The density of the lines in the diffraction pattern of any substance depends upon the amount of that substance in the sample. Quartz has four lines that are sufficiently intense for quantitative measurement. By the use of an internal standard[77] and a microphoto-

[67] Ward's Natural Science Establishment Inc., Rochester, N. Y.

[68] E. S. Larsen and H. Berman, *U. S. Geol. Survey Bull.* No. **848** (1934).

[69] M. N. Short, *U. S. Geol. Survey Bull.* No. **914** (1940).

[70] A. N. Winchell, *Elements of Optical Mineralogy.* Wiley, New York, 1931.

[71] A. N. Winchell, *Artificial Inorganic Solid Substances or Artificial Minerals.* Wiley, New York, 1931.

[72] E. S. Dana, *A Textbook of Mineralogy.* Wiley, New York, 1932.

[73] E. M. Chamot and C. W. Mason, *Handbook of Chemical Microscopy.* 2nd ed., Wiley, New York, 1938.

[74] H. L. Ross and F. W. Sehl, *Ind. Eng. Chem., Anal. Ed.*, **7**, 30 (1935).

[75] W. D. Foster and H. H. Schrenk, *U. S. Bur. Mines Repts. Investigations* No. **3368** (1938).

[76] J. D. Hanolvalt, H. W. Rinn and L. K. Freval, *Ind. Eng. Chem., Anal. Ed.*, **10**, 457 (1938).

[77] J. W. Ballard, H. I. Oshry and H. H. Schrenk, *U. S. Bur. Mines Repts. Investigations* No. **3520** (1940).

FIG. 11. X-ray diffraction patterns of quartz in dolomite (a), pure quartz (b), and quartz in albite (c) (*courtesy H. H. Schrenk, U. S. Bureau of Mines*).

meter for measuring the relative density of the lines of the unknown and those of the internal standard, quantitative measurements of satisfactory accuracy may be obtained.[78] For good results, samples for analysis must be ground to 200 mesh or smaller and after the internal standard has been added the sample must be further ground and mixed. A special type of stainless steel ball mill, using methanol as a dispersing agent, has been used for this purpose, being operated 24 hours.

A recent development has been the advantageous use of Geiger counter spectrometers for determining the densities of the lines in the diffraction pattern, with better resolution in some instances of partial overlapping of lines, and, in some cases, obviating the need for an internal standard.

BACTERIA

The sampling and evaluation of bacteria in the atmosphere have received much attention in recent years, but the procedures are still in an experimental stage. There are several collection methods that employ the principle of impingement: such as the air centrifuge,[79] the funnel device,[80] the slit impinger,[81] Sharf's prescription bottle sampler,[82] the sieve device,[83] and the exposed agar plate or petri dish method. Simple Folin scrubbers,[84] beaded scrubbers,[85] and atomizer scrubbers[86] have

[78] J. W. Ballard and H. H. Schrenk, *U. S. Bur. Mines Repts. Investigations* No. **3888** (1946).
[79] W. F. Wells, *Am. J. Pub. Health*, **23**, 58 (1933).
[80] A. Hollaender and J. M. DallaValle, *U. S. Pub. Health Repts.*, **54**, 574 (1939).
[81] R. B. Bourdillon, O. M. Lidwell, and J. C. Thomas, *J. Hyg.* **41**, 197 (1941).
[82] R. Schneiter, A. Hollaender, B. Caminita, R. W. Kolb, H. F. Fraser, H. du Buy, P. A. Neal, and H. B. Rosenblum, *Am. J. Hyg.*, **40**, 136 (1944).
[83] H. G. du Buy and L. R. Crisp, *U. S. Pub. Health Repts.*, **59**, 829 (1944).
[84] L. F. Rettger, *J. Med. Research*, **22**, 461 (1910).
[85] S. M. Wheeler, G. E. Foley, and T. D. Jones, *Science*, **94**, 445 (1941).
[86] S. Moulton, T. T. Puck, and H. M. Lemon, *Science* **97**, 51 (1943).

also been used and they give much higher results than the impingement methods. The size of the organisms and their tendency to form clusters or clumps have an important bearing on the relative collection efficiency of a method. With the scrubbing devices any clumps or clusters are broken up, whereas they may register as one colony by impingement. A discussion of these devices has been published;[87] it includes a comparison of their performances.

The sampling media[88] have a still greater influence upon results, not only as regards standard practice, in order to try to establish some means of comparison of results, but of even more importance, as regards the retention and growth of pathogenic organisms of interest in air sanitation work, and the inhibition of nonsignificant saprophytes that interfere with the desired bacterial counts.

No satisfactory index of bacterial contamination of the air has been recognized, either in type or number of bacteria. In the present state of development these problems are largely of a research nature, but doubtless within the next few years methods of evaluation and control of atmospheric bacterial contamination will have reached standardization levels.

[87] H. G. du Buy, A. Hollaender and M. D. Lackey, *U. S. Pub. Health Repts., Supplement* No. **184** (1945).
[88] R. Schneiter, J. E. Dunn and B. H. Caminita, *U. S. Pub. Health Repts.*, **60**, 789 (1945).

CHAPTER NINE

Radiant Energy and Radium

LEON F. CURTISS

I. Fundamental Concepts of the Production of Injury by Radiation

A. IONIZATION AS CAUSE OF INJURY

Radiant energy produces undesirable effects in the human body whenever it is absorbed in excess of certain amounts to which the human organism has been accustomed in its natural surroundings. These undesirable effects may arise in different ways, may become evident in a variety of manifestations; but, regardless of the particular type of radiation producing them, the basic process in the human system by which injuries from radiations occur is much the same. This is more readily understood when the effect of various types of radiation on individual living cells is investigated. Such study reveals that the injury to cells is proportional to the ionization produced in the cell. Therefore, injuries result only when the radiation releases ions within the cell structure. So far as the effect on the cell is concerned, it does not matter greatly whether these ions are produced indirectly by secondary electrons from x-rays or gamma rays; or directly, by primary particles, as in corpuscular radiation of such rays as beta rays and alpha rays. The effects on the human body, however, may vary considerably depending on the type of radiation, the way it is applied, and the kind of cells that are destroyed, or injured, by the effects of the ionization that is produced by the radiation.

B. TARGET THEORY

From investigations of the injuries produced in simple forms of life by radiation it is also found that all parts of the cell are not equally sensitive. There is a definite region, sometimes referred to as the target area, which, when sufficient ionization is produced in it, releases reactions fatal to the entire cell. This explanation forms the fundamental concept in the target theory of the action of radiation, which has been quite successful in explaining the observations when bacteria are irradiated and the lethal effects measured. The application of this theory to higher forms of life is complicated by the secondary physiological reactions that are set up in the tissues by the destruction of some of the component cells. Furthermore, it appears that under

certain conditions multiple impacts on the target area are required in order to produce lethal effects. However, extensions of this method of approach to the problem meet with increasing success in explaining the effects of radiation in many-celled tissues.

C. INJURIES IN HIGHER FORMS OF LIFE

When we come to more complicated organisms and, in particular, to the human body, the lethal effect of ionization on individual cells plays the dominating role in the injuries produced. An additional factor enters, however, in that the various groups of cells in the organism co-operate to repair the damage so that the destroyed cells may be replaced. Consequently the human body may be exposed repeatedly to intensities of radiation that destroy many individual cells without producing a permanent bodily injury, if sufficient time for recovery intervenes between exposures, no one of which is sufficient to overburden the restorative processes. It is on this fact that the commonly accepted ideas regarding tolerance limits of exposure to radiation are based. However, not all types of cells in the human body can co-operate to repair damage. For example, parts of the eye, brain, and most muscular tissues are unable to produce new tissue to replace that which has been damaged.

When we say that various types of ionizing rays produce basically the same biological effects, we must limit this statement to the nature and not the degree of the effect. If, for example, the target theory of cell injury is correct, it is readily conceivable that radiant energy in the form of a massive high-speed corpuscle, such as an alpha ray, leaving a dense column of ions in its wake, will have a much better chance of being fatal to more cells, and even a greater variety of types of cells, than an ionizing agent that produces relatively few widely spaced groups of ions along its path, such as the swift beta particle.

D. GENETIC EFFECTS OF RADIATION

In recent years biological investigations have revealed that types of injury may occur to cells in the human body that are more complicated than the outright destruction of a cell, or a group of cells. This new information has come from the study of radiation as related to genetics. These studies show that radiation produces a definite effect on the structure of the chromosomes, the threadlike structures in the cell nuclei that control the characteristics of a cell, and, if it is a cell that later divides, control also the characteristics of its descendants. This control is accomplished by an intricate system of elements, called genes, in the chromosomes, it being assumed that a normal cell has a definite set of chromosomes with an equal number of genes arranged in a definite way in the chromosomes for each type of cell. The effect of the radiation is to alter or destroy either the chromosomes, or genes, or both.[1] The result is a mutation in which the subsequent cells resulting from division of the affected cell are different from the parent cell. This effect has been proved many times experimentally, using organisms that reproduce

[1] G. Failla, *J. Applied Phys.*, **12**, 279 (1941).

rapidly, such as the fruit fly. For man this genetic effect of radiation has two important implications. In one case, cells altered in this way may produce abnormal organs in the body. In the other, if the change has been produced in a germ cell, subsequent offspring may develop abnormally. The importance of these possibilities becomes more prominent in the light of the knowledge that mutational changes are irreversible; there is no recovery. And if a certain dose of radiation will produce a certain percentage increase in mutations, it does not matter whether this dose is administered over a few days or a few years.[2] This is illustrated in Figure 1, which shows that there is no variation in the mutation rate for a given dose administered over a variety of periods.

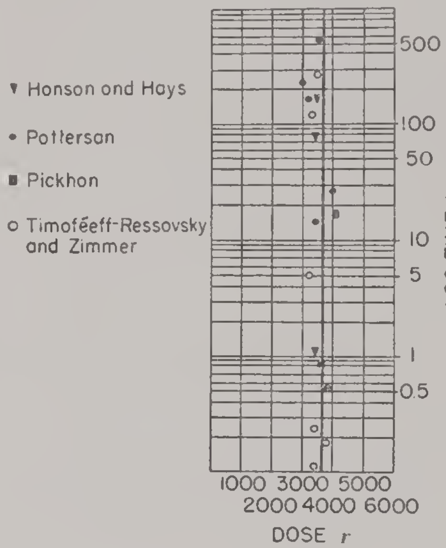


FIG. 1. The heavy vertical line, drawn to represent an average of the observations, shows that the mutation rate for *Drosophila melanogaster* is independent of a time factor when a given dose of radiation is administered over various different periods of time.[2] From radiation experiments of the various authors listed, the dose of radiation in *r* is calculated which will produce an increase of 10 per cent in the sex-associated mutation rate and plotted against the time selected for irradiation. For convenience, a logarithmic scale is used for time. These doses fluctuate within statistically expected limits about the value of 3,600 *r*.

An additional fact, which now seems well established, is that the percentage change in mutations is directly proportional to the dose.[2] This is shown in Figure 2. Therefore, taking these two properties together we see that from the standpoint of genetics the effects of radiation are permanently cumulative. A very weak exposure over many years, therefore, will be just as injurious genetically as a single massive exposure administered at one time.

These facts have an important bearing on tolerance limits of exposures of individuals to radiation, particularly to penetrating radiation such as x-rays and gamma rays, where germ cells may be affected. It is obvious that so far as man is concerned no information is available, or will become available within present generations, to determine what intensities of radiations can be tolerated over a life span without producing a noticeable change in the mutation rate. This problem is complicated by the fact that most mutations are recessive and result in deleterious changes. Consequently, individuals who escape any immediate effects of exposure

[2] Timoféeff-Ressovsky, Zimmer, and Delbrück, *Nachr. Ges. Wiss. Biol. Göttingen, 1,* No. 13 (1935).

to radiation may be responsible for undesirable hereditary changes in later generations. It should be noted that the recessive nature of the mutations is such that they will not ordinarily appear in the first succeeding generation. Therefore, the production of normal offspring by individuals exposed to radiation does not indicate

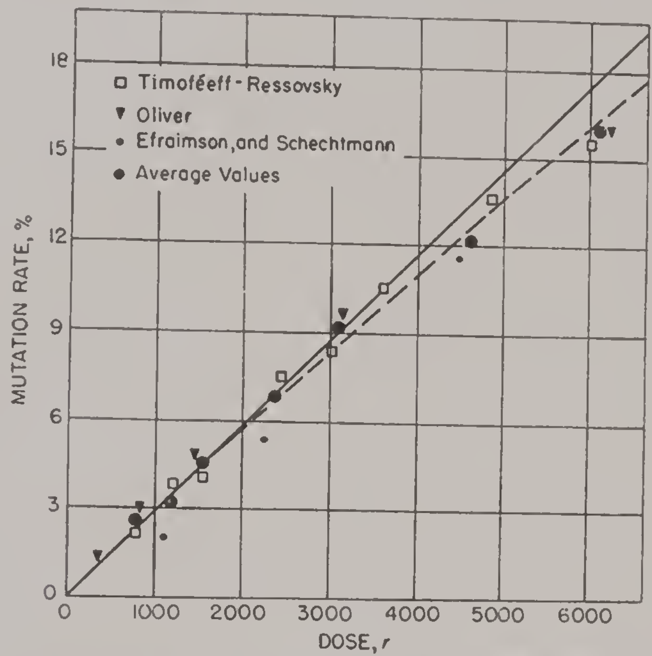


FIG. 2. The solid line reveals the direct proportionality of rates of sex-associated mutations in *D. melanogaster* to dose of x-rays. The effect of the saturation curve on the direct proportionality is indicated by the dotted line. Observed points are by various authors, as listed.

that no injury has occurred. The results may appear in later generations. A certain low mutation rate is normally present, but no marked increase could be tolerated.

E. VISIBLE EVIDENCE OF INJURY FROM RADIATION

The generally known injurious effects of radiant energy are customarily classified under the type of radiation that produces them. This custom has arisen not so much because the effects are different, since basically they are not, but for the convenience of those dealing primarily with one particular type of radiation in the application of radiant energy to some particular problem. Since this chapter is concerned primarily with hazards that arise in industrial processes where radiation is present, we shall discuss the subject under the headings of gamma rays, x-rays, infrared radiation, ultraviolet radiation, and corpuscular radiation. In view of the fact that radium poisoning applies primarily to one industry, that of painting radium dials, it will be discussed in a separate section, although it is also a special case of injury from radiation, which occurs in the same basic way as all others.

The disruptive effects that radiation can produce in living cells result in a great variety of bodily injuries in persons exposed to the radiation. These effects depend on the type of radiation and particularly its penetrating power, on the method of

exposure, whether local or over the whole body, and on the parts of the body affected. Injuries range all the way from a slight erythema to radiation osteitis, which may be followed by crippling bone lesions and osteogenic sarcomas, which soon prove fatal. In many cases anemias occur that may be aplastic or regenerative depending on the cell groups affected, which, in turn, frequently depend on the type of radiation and its mode of application to the body. Fatal leucopenias also have been observed.

Admittedly, these and other similar symptoms and disabilities are of importance chiefly to the physician who may be called upon to treat a person suspected of suffering from an overexposure. Also, the studies of persons affected by radiation have resulted in valuable additions to the general knowledge of bodily functions. They are cited here primarily to indicate the severity of injury that may result from injudicious exposures of the body to radiant energy. In most situations, sufficient information is now available so that protective measures can be set up to prevent all but the foolhardy, or grossly ignorant, from suffering any of the more serious consequences of overexposure. It will be our aim to point out these protective procedures in the course of the detailed discussions of the various industrial hazards that involve radiant energy.

II. Penetrating Ionizing Radiation

A. TYPES OF EXPOSURE AND INJURIES

The penetrating radiations typified by x-rays and gamma rays produce effects on the human body which are similar. Since, in fact, the spectrum of x-rays has now been extended to overlap the gamma ray spectrum, there is no sharp boundary between them either as regards their physical nature or the physiological effects they may produce. The most prominent difference that they exhibit in comparison with other types of radiant energy, so far as physiological effects are concerned, is that they can produce effects throughout the whole body at one time. This ability accrues from the low coefficient of absorption, which permits this type of radiation to pass entirely through any part of the body with only a moderate diminution of intensity. Naturally, it is still possible to expose only a part of the body, as by extending the hand into a well-defined beam of x-rays, and in practice local overexposure may readily occur. However, such local overexposures are much more apt to be accidental, or the result of carelessness, whereas the whole-body exposure originates from the difficulty of screening this type of radiation. Consequently workers engaged in application of x-rays and gamma rays in industrial plants are subject to both types of exposure. Since these radiations are chiefly distinguished by the manner in which they are generated and applied, they will be discussed as a group where phenomena common to both are concerned, with separate detailed discussion of conditions peculiar to each.

1. Latent Period

From our introductory discussion of current ideas as to how radiation can produce injury to living tissue, it is apparent that the full effects of irradiation will

not be manifest at once. The destruction of cells in a complicated assembly such as human tissues will set in motion a train of events that may reach a culmination weeks or months after the exposure. Since not every cell in the tissue affected is destroyed by radiation, as would be likely to be the case in a burn produced by excessive temperature, the tissue begins to exhibit the deficiencies resulting from the occasional destruction of isolated cells only after a period of development during which the injured or obliterated cells restrict normal growth. Consequently, one of the most striking characteristics of injuries arising from gamma rays or x-rays is the latent period that always follows, between irradiation and the visible manifestations of its effects. We are all familiar with the same general process in ordinary sunburn, in which the burn develops several hours after exposure. In the case of gamma rays and x-rays, this latent period extends to several days, even when the effect produced is in the surface tissue, as in an erythema, and many effects may develop much later. This is particularly true of malignancies that originate from exposure to radiation.

Because of this latent period there is no warning of injury at the time of exposure, even for local injuries that are severe enough to develop into painful and crippling burns. It is only by habitual regard for definite procedures that persons using radium and x-rays can escape injuries of various kinds. These injuries may be a slight or severe erythema and from greater exposures, a deep deterioration of the underlying tissue resulting in permanent deformity. In another category are injuries such as keratoses, malignant growths, and even deep-seated cancers that develop over periods of years and do not produce visible effects, in some instances, until they have reached an advanced stage of development. One very important difference between the effects of x-rays and of gamma rays in producing malignancy is that overexposure of the skin to gamma rays does not produce epithelioma until the skin has been broken by subsequent injury. In burns by x-rays generated by moderately high voltage these malignancies may develop without further stimulus. We also know that large doses of penetrating radiation, whether given in one sitting or over a long period, will produce noticeable disturbances in the blood count. If the dose is sufficiently large, anemia or leucopenia may result. Either disease may reach a fatal stage unless the exposure is interrupted and restorative measures applied in time.

2. Tolerance Dose

Whereas local injuries from gamma rays and x-rays can be avoided by careful habits of work and suitable protective screens, the prevention of excessive exposure of the whole body must be based on a knowledge of the dosage that will not produce detectable injury. Admittedly the information on this subject is somewhat scanty, but evidence has accumulated over the past thirty years to show that exposures of 0.1 roentgen per 8-hour day for long periods of time produce no evident injuries to health. This figure has recently been revised by the International Commission on X-Ray and Radium Protection to a value of 0.02 *r* per day. This revision was partially intended to take care of genetic injuries and may be subject to further revision as additional information on this subject becomes available. The roentgen

(r) is defined by the Fifth International Congress of Radiology as "the quantity of x-radiation or gamma radiation such that the associated corpuscular emission per 0.001293 gram of air produces, in air, ions carrying 1 electrostatic unit of quantity of electricity of either sign." Thus, this unit is based on the rate of production of ions in air, which is in general a direct measure of the ability of the radiation to produce biological effects.

3. *Methods of Measuring Exposure*

It is obvious, from the definition of the roentgen, that the exposure, in terms of a tolerance dose measured in this unit, can be evaluated only by a device that will either measure the number of ions produced in air or give an indication that is proportional to this quantity. It is also evident that measurements in terms of tolerance dose can be made by measuring the rate of production of ions as roentgens per second and multiplying by the time of the total exposure, in which this rate is assumed constant over the period. On the other hand, the total number of ions produced can be added up over the period, thus giving directly the roentgens for this period. Instruments are available which operate on each of these principles and each method has some advantages for particular situations. Where the intensity of the radiation is constant, or where it is desired that the rate of exposure shall not exceed a given value, instruments that indicate roentgens per day are not only applicable, but will give immediate information regarding rate of exposure and any changes in this rate. On the other hand, if the intensity of the radiation fluctuates in a manner not readily controlled, and it is desirable to know the total exposure for a definite period of time, the integrating type of measuring instrument is preferable. This instrument also possesses the advantage that compact ionization chambers may be devised that can be carried on the person of a worker and thus record the total exposure as he goes about his tasks. The integrating method does not, however, reveal at what point he received the greatest amount of radiation—as a guide to additional protective measures—in case the dose is found to be excessive at the end of the period. This can best be done by a rate-of-dosage type of meter.

Ionization method. The portable ionization chamber is illustrated in Figure 3, which shows diagrammatically the general construction and method of operation. A cylindrical ionization chamber, C, is used to measure the ionization for the desired period of time. This chamber may, for some purposes, be only slightly larger than a fountain pen. It must be provided with the best quality of insulation. For use, it is inserted in a bushing at the side of the case, as shown in the diagram. This brings the central electrode in contact with the rod extending from the insulated fiber of the electrometer, E. By pushing down the key, K, the central rod of the chamber and the insulated fiber of the electrometer are brought to a definite voltage supplied by a suitable source of potential mounted inside the case. The corresponding reading of the electrometer is the zero of the instrument for measurements of dosage. The chamber, C, can now be removed and carried by an individual throughout the day. At the end of the period of exposure it is again inserted in the receptacle on the case

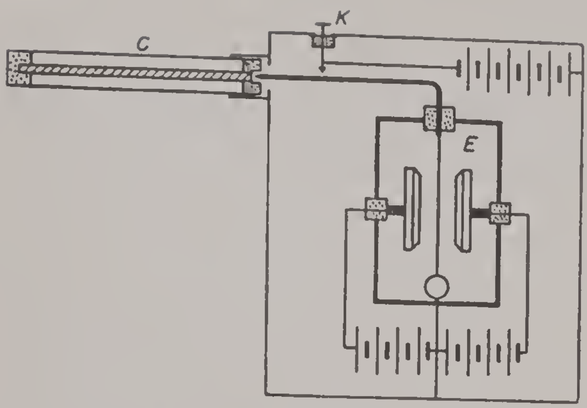
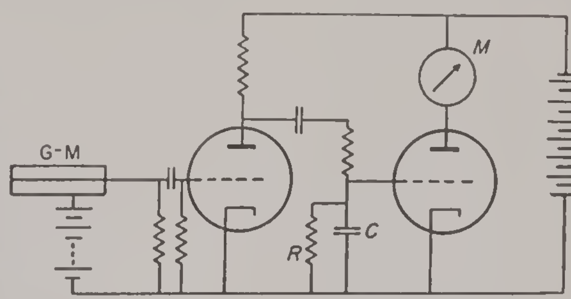


FIG. 3. Schematic diagram of the probable integrating ionization chamber for measurements of exposures to gamma rays and x-rays. K—charging key, C—detachable ionization chamber, E—string electrometer.

of the instrument, and the deflection of the electrometer recorded. The electrometer is so calibrated in connection with the chamber that this final reading gives directly the dose in roentgens. This measurement is based on the assumption that the decrease in voltage of the central electrode of the chamber has been produced entirely by ionization of the air in the chamber during the period of exposure. With care in selection and preparation of the insulators, this assumption can be realized sufficiently for the types of measurements under discussion. Instruments of this type are available commercially, such as the Victoreen minometer, in which all potentials are derived from an ordinary outlet from the lighting circuit.

Use of Geiger-Müller counter. For direct determination of the rate at which a dose is administered, a suitable modification of the Geiger-Müller counter has found extensive use. The principle of this device is illustrated, so far as essential features are concerned, in Figure 4. The sensitive element in this device is the Geiger-Müller counter tube. Its action depends on the release of ions from parts of the tube or gas by the gamma radiation or x-radiation as it traverses the counter. Usually a single pair of such ions produces sufficient ionization to cause a discharge between the cylinder and central wire of the counter tube. This discharge results in a sudden rise of voltage of the central wire. The voltage pulse can be amplified by a suitable vacuum-tube circuit. In Figure 4 the vacuum-tube circuit associated immediately

FIG. 4. Simplified diagram of vacuum-tube circuit for use with a Geiger-Müller counter tube to measure the rate of exposure to gamma rays and x-rays. G-M—counter, M—indicating meter, C—condenser in which received pulses are accumulated, R—resistor permitting charge to leak from condenser C, so that the potential across this condenser assumes a constant value for a constant rate of pulses.



with the counter serves to level, as well as amplify, the pulse. It may consist of one or several vacuum tubes connected in a variety of ways. For simplicity a single tube is shown for this part of the circuit in the figure. Sufficient rectification is also introduced into this part of the circuit so that the pulses emerging are undirectional when reaching the condenser, C. Therefore, a small quantity of charge is added to this

condenser for each pulse. Since the resistor, R, is connected across this condenser the value of the potential across the condenser will finally assume a constant value for a constant average rate of pulses. The second vacuum-tube circuit is connected as a voltmeter so that the potential can be read on the condenser by means of the meter, M, in the plate circuit. Thus, in a relatively short time, depending on the value of the product RC, after the Geiger-Müller counter has been introduced into the field of radiation the meter, M, will indicate the intensity of the radiation. This meter may be calibrated in roentgens per day, or some similar unit. In the same way the meter will follow changes in this intensity. This change may occur as a result of alterations in the source of radiation, or of moving the instrument to different positions in relation to the source.

Although the Geiger-Müller counter is most effective as an indicator of the rate of exposure, the circuit represented also may be converted into an integrating instrument by removing the resistor, R, from across the condenser. Then, the voltage on the condenser will be proportional to the number of pulses that have arrived since the condenser was last discharged. Electrical circuits associated with Geiger counters are sensitive to electrical disturbances. Therefore, they can be used in connection with x-ray installations only when carefully shielded. They also must be specially constructed and calibrated for use with x-rays of each separate spectral range. These difficulties are not ordinarily encountered in measurements of radioactivity.

Use of photographic film. A very practical method for measuring exposure to gamma rays and x-rays is by use of photographic films. With care in calibration and selection of films, the photographic method is capable of considerable accuracy. Very misleading results are obtained, however, when proper precautions are not observed. The use of x-ray dental films is very convenient, since they may be worn by an operator through a period of work extending to several days and thus provide an over-all integration of the dose received. For proper evaluation of the results, the developed films must be photometered in comparison with films from the same lot which have received known exposures to radiation of the same quality as that under investigation. Figure 5, reproduced from a paper by Fricke and

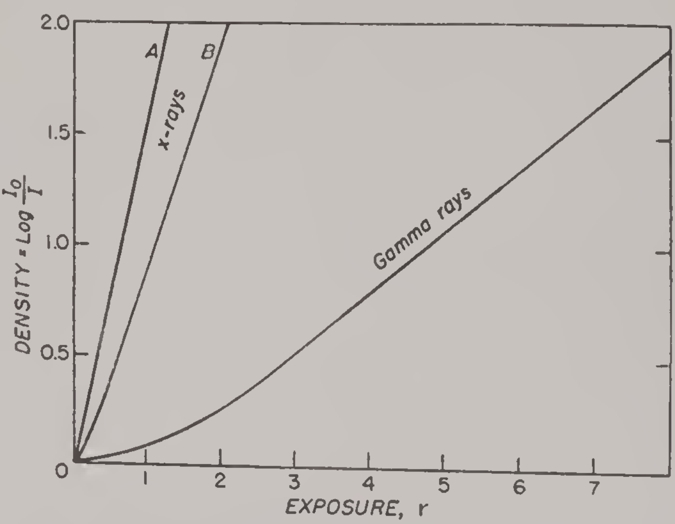


FIG. 5. Curves showing the variation in blackening in the same type of film for equal doses of x-rays and gamma rays. A—80 kv. x-rays, no filter, B—200 kv. x-rays, filtered by 2 mm. of copper. Gamma rays filtered by 6.8 mm. of gas.

Williams,[3] shows curves that illustrate the differences in photographic blackening for the same quantitative exposure to radiations of different quality.

4. Blood Counts as Index of Injury

In spite of all due caution in manipulations and proper measurements to insure that the tolerance dose is not exceeded, it is conceivable that some individuals may be more than ordinarily sensitive to radiation, or may accidentally receive excessive exposures. The best check on such possibilities known at present is the use of regular blood counts. It is well established that characteristic changes occur in the blood picture as the result of irradiation by gamma rays and x-rays. The only difficulty is that these changes frequently become definitely recognizable only after much injury may have been done. Nevertheless, the use of the blood count is generally recommended. Furthermore, the results of the counts, which always should be made by the same technician for each person under observation, and under similar conditions, should be interpreted by an experienced hematologist. These blood counts should include: hemoglobin test, red, white, and differential counts, including the percentages of polymorphonuclear cells, small, and large lymphocytes (separately), eosinophiles, and basophiles. Blood platelet, sedimentation, and coagulation tests also are of value.

A guide in determining departures from a normal blood count is provided by Table 1, as given by Goodfellow,[4] who has investigated the effects on the blood

TABLE 1

Typical Blood Counts as Reported by Various Authorities

Type of cell		Mottram	Schilling	Dyke	Shaw	Emerson	Simpson	Simpson	Taylor, *Practice of Medicine*
								Widest variations observed	Accepted normal limits (in morning)
Total W.B.Cs.	Max.	—	8,000	8,500	9,650	8,000	11,200	18,100	9,000
	Min.	—	6,000	5,500	3,200	6,000	5,100	2,800	4,000
	Mean	—	—	—	5,987	—	—	—	—
Neutrophiles	Max.	13,000	—	75%	69.8%	70%	8,920	13,100	5,000
	Min.	3,000	—	60%	37.0%	63%	2,920	1,600	2,500
	Mean	—	67%	—	53.2%	—	—	—	—
Lymphocytes	Max.	6,000	—	40%	51.2%	30%	2,440	4,040	3,000
	Min.	1,500	—	25%	22.6%	20%	1,010	820	1,500
	Mean	—	23%	—	36.8	—	—	—	—
Monocytes	Max.	—	—	7%	10.0%	10%	—	—	600
	Min.	—	—	2%	3.0%	—	—	—	20
	Mean	—	6%	—	6.7%	—	—	—	—
Eosinophiles	Max.	—	—	2%	6.4%	2%	—	—	400
	Min.	—	—	0	0.0%	—	—	—	20
	Mean	—	3%	—	2.5%	—	—	—	—
Basophiles	Max.	—	—	1%	2.0%	0.5%	—	—	100
	Min.	—	—	0	0.0%	—	—	—	0
	Mean	—	1%	—	0.7%	—	—	—	—

[3] R. E. Fricke and M. M. D. Williams, *Radiology*, **34**, 560 (1940).

[4] D. R. Goodfellow, *Brit. J. Radiol.* **8**, 669, 752 (1936).

count of exposure to gamma rays. He finds that the only sign of overexposure common to all workers is a leucopenia, due to a reduction of circulating neutrophiles. There is evidence that different individuals vary in susceptibility to the effects of irradiation. Those who are more sensitive exhibit an absolute lymphocytosis with an absolute leucopenia as the first sign of overexposure. Others, less sensitive, under the same conditions show a lymphocythemia with a monocytosis. Eosinophilia is frequently seen as a result of overexposure, and abnormal or embryonic leucocytes have been observed. Goodfellow states that vacations of less than four weeks do not appear to be of value in restoring leucocyte counts to normal.

This general survey so far has dealt with conditions common to the use of both gamma rays and x-rays. To make suggested protective rules simpler and more accessible they will now be listed separately, taking into account the more detailed differences in the methods of utilizing these two types of radiations in industrial applications.

B. PROTECTION FROM GAMMA RAYS

1. *Pre-employment Examination*

The first rule for safeguarding workers engaged in handling radium is that only those who have been found by thorough medical examination to be in excellent health should be employed. This precaution not only is a safeguard against assigning radium exposure as a cause of some ailment already in progress before any exposure, but also it guards against the employment of persons with abnormalities, such as unusual blood picture, chronic anemia, etc. In this way, the number of individuals unusually susceptible to radiation injury also will be reduced. Finally, it establishes a reference for future medical examinations of the individual, so that any change in health and symptoms that may occur can be observed and recorded.

It is also important to explain to a prospective employee for work with radium the nature of the proposed work, the type of hazards involved, and the details of protective rules, especially those that apply with particular emphasis to the job in question.

2. *Protection of Personnel*

The protection of radium workers involves the prevention of overexposure, both locally and over the entire body. The total exposure is most readily reduced through lowering the degree of exposure by taking advantage of the inverse-square law. The next factor in order of importance is reduction of time of exposure. Therefore, provisions should be made so that all operations involving radium can be carried out with all parts of the worker's body as far from the radium as is consistent with the nature of the task, and so that operations can be carried out in the shortest time. In this connection, it may be well to point out that under no circumstances should a concentrated preparation of radium or other radioactive substance come in direct contact with any part of the worker's body, especially the fingers. A further precaution is that in intervals between necessary handling of radium no worker should

be allowed to remain in the vicinity of the source of radiation. This rule applies also to those who are not directly concerned with such work. One of the advantages of the use of radium in radiography is that it requires no adjustment or supervision during exposure, and this avenue of protection should be used under all circumstances.

Regular medical examinations should be given employees engaged in handling radium. This examination should include a blood count as well as a careful check of each of the known possible symptoms of overexposure to radiation. In particular, an examination for evidences of injury to fingers by radiation should be made. In this way, carelessness in the use of fingers in handling radium may be detected. The frequency with which medical examinations should be made depends somewhat on the conditions of work. Table 2, taken from Handbook H23 of the National Bureau of Standards, *Radium Protection,* shows permissible daily exposures with contingent safe distances of a technician during these exposures. If conditions are such that workers are receiving greater doses of radiation than indicated by this table, a medical examination should be made every month.

TABLE 2

Safe Working Distances from Radium

Total daily exposure, milligram-hours	Safe distance		Total daily exposure, milligram-hours	Safe distance	
	Meters	Feet		Meters	Feet
100	1	3	800	2.5	8
200	1.5	4	1600	3.5	11
400	2	6	3200	5	15

We pointed out in the introduction to this chapter that, except for injury to genes, bodily injuries from radiation will show recovery, providing the exposure has not been excessive. For this reason, it is important that those working more or less continuously with radium should be required to take vacations where they will be outdoors as much as possible. For a technician who works with radium constantly, this vacation should be at least one month. An alternative is rotation of employment so that no technician is so employed more than six months of a year, in which case the vacation period may be reduced.

3. *Storage of Radium*

The storage of radium in a way to protect employees against exposure often presents something of a problem, particularly where large amounts are involved, as is frequently the case in industrial radiography. In general, the inverse-square law provides the most effective and most economical means of solving this problem. However, a certain amount of lead, or its equivalent, shielding is usually required. The thickness of this shielding in any particular direction will depend upon the distance to the person to be protected, the period of time for which protection is required, and the effect that the required protective screen may have on the intensity

of the radiation in other directions where protection may be required. In other words, the scattered radiation must be taken into account and in some cases this can be done only by actual measurement. In any case the combined protective arrangements must reduce to the tolerance dose the whole body exposure.

Storage vaults for radium should be designed with as small an interior cavity as will comfortably accommodate the radium. Not only is this more economical but, by reducing the size of the exterior it reduces the amount of scattered radiation in the vicinity. Where material other than lead is used for this vault, the lead equivalent (see Table 6) must be known under conditions similar to those in which the material is to be used.

In general, the lead equivalent for gamma rays can be computed by multiplying the thickness of the material by the ratio of its density to that of lead. In computing required thicknesses, it is advisable to increase the thickness of the material by about 50 per cent of the value obtained in the above computation.

When designing storage vaults for relatively large amounts of radium, it is desirable to provide separate lead screening for individual preparations, or small groups of preparations. This reduces the exposure of the technician who must remove the radium from the vault. It is even more important to adopt a convenient and methodical arrangement for storage so that the time required to select and remove a given preparation is reduced to a minimum. Identifying numbers, readily legible at some distance, on various compartments are an illustration of one method of expediting the selection of a preparation. Similar numbers on the preparations themselves, when these are of sufficient size, or a color code for various types of preparations, also can be employed. In no case should the dose received during the selection and removal of preparations exceed a small fraction of the permissible daily dose.

4. *Manipulation*

It is difficult to enumerate, within the space available, the various accessories and arrangements that can be employed to reduce exposure of the technician handling radium, particularly in the large amounts ordinarily used in radiography. Remote control devices of a great variety of types have been used, and new ones are constantly being devised to permit the operator to place the radium in the desired position while remaining at a safe distance. Long cords are frequently used with guides variously arranged to permit the radium container to be pulled into position and removed. The important point is to make certain that such arrangements are used wherever desirable. However, remote control devices should not be so awkward to manipulate that they greatly increase the time required for manipulation and thereby defeat their purpose. Fortunately, it is possible to check by actual measurements the exposure received during a particular operation: thus, various methods can be compared in respect to exposure.

It should never be assumed that rules of procedure and specific instructions to technicians and assistants are sufficient to preclude possibility of injury. Wherever large amounts of radium are handled, there may be situations that require excessive

exposures, and these may even occur with unexpected frequency. Therefore, operators should be under the constant supervision of some one trained to detect incipient injuries from radiation so as to prevent more severe consequences. Frequently a rigorous supervision, to see that proper procedures are followed, may be necessary. In addition to inspection of hands and fingers, a careful review of the blood count is imperative where large exposures may occur. Furthermore, it must be remembered that radiation osteitis, which eventually may lead to an osteogenic sarcoma, can be present for some time without any change in the blood picture. Such a condition can be detected only by x-ray of the bone structure.

5. *Exposure Table for Gamma Rays*

As a guide in estimating exposures and in arranging safe conditions, Table 3 shows safe distances, in meters, for various amounts of radium, when screened by

TABLE 3

Safe Distances in Meters for Continuous Exposure Daily for Eight Hours[a]

Lead thickness, cm.	Radium, mg.														
	0.1	1.0	2	4	10	20	40	100	200	400	1000	2000	4000	10,000	100,000
0.1	0.08	0.25	0.36	0.5	0.8	1.2	1.6	2.5	3.6	5	8	12	16	25	80
0.5	0.07	0.22	0.31	0.44	0.7	1.0	1.4	2.2	3.1	4.4	7	10	14	22	70
1.0		0.18	0.26	0.36	0.6	0.8	1.2	1.8	2.6	3.6	5.8	8.2	11.6	18	58
2		0.14	0.2	0.28	0.44	0.6	0.9	1.4	2	2.8	4.4	6.2	8.8	14	44
3		0.11	0.16	0.22	0.34	0.5	0.7	1.1	1.6	2.2	3.4	4.8	7	11	35
4			0.11	0.16	0.25	0.35	0.5	0.8	1.1	1.6	2.5	3.5	5	8	25
5				0.12	0.2	0.3	0.4	0.6	0.9	1.2	2	2.8	4	6.2	20
6				0.1	0.16	0.23	0.3	0.5	0.7	1	1.6	2.3	3	5	16
8					0.1	0.14	0.2	0.3	0.4	0.6	1	1.4	2	3	10
10							0.13	0.18	0.27	0.37	0.6	0.83	1.3	1.8	6
12									0.17	0.25	0.4	0.6	0.8	1.3	4
14											0.26	0.4	0.5	0.83	2.6
16											0.17	0.25	0.35	0.54	1.7
20														0.3	0.9

[a] Based on daily dose of 0.1 *r* per 8 hours.

thicknesses of lead from 1 mm. to 20 cm. This table is based on a tolerance dose of 0.1 r per 8-hour day. For a tolerance of 0.02 r per 8-hour day, these distances would be multiplied by $\sqrt{5}$.

6. Protection of Messengers

It is occasionally necessary to send radium short distances by messenger. In such cases it is essential to provide special packing, in addition to the lead container, to prevent possibility of local injuries. An outer container is used large enough so that all points on the outside are a certain minimum distance from the lead container (see Table 4). When dispatching a messenger, it is desirable to give instructions regarding prompt delivery to destination, since the figures in the table are intended only to prevent local injury for short exposures. It may be well to mention that a messenger carrying radium should perform no other errands that would delay him or take him from his direct route; and in no case should he carry undeveloped photographic film.

TABLE 4

Required Effective Dimensions of Outer Packages Around Inner Ones to Provide Safety to Messengers

Quantity of radium, mg.	Thickness of lead, cm.	Minimum distance to surface, cm.	Quantity of radium, mg.	Thickness of lead, cm.	Minimum distance to surface, cm.
10	0.1	3.5	100	0.1	11.1
20	0.1	5.0		0.5	9.8
	0.5	4.4		1.0	8.3
	1.0	3.8	200	0.1	16
50	0.1	8		0.5	14
	0.5	7		1.0	12
	1.0	6			

7. Transportation by Common Carrier

Shipments of radium, radon, or similar radioactive substances, including artificially radioactive elements, through the mail are prohibited in the United States by postal regulations. This regulation is intended to prevent fogging of photographic films. Express companies will accept such material for shipment if it is plainly marked to indicate that the package contains radium, with a statement on the label of the amount of radium and the thickness of the lead containers. Table 5 shows the thicknesses of lead required by express companies for various amounts of radium, depending upon the time in transit. Advance arrangements must be made with local agents for amounts in excess of 100 mg.

TABLE 5

Thicknesses of Lead Required for Shipment of Radium by Railway Express and Allowable Hours in Transit[a]

Quantity of radium, mgs.	Thickness of lead, in.								
	0.25	0.5	1	1.5	2	2.5	3	3.5	4
	Allowable hours in transit								
Under 15 mg.	40	60	110						
15 mg. and under 25	20	30	55	110					
25 mg. and under 35	14	20	36	73	146				
35 mg. and under 45	10	15	28	55	110				
45 mg. and under 55		12	22	44	88	170			
55 mg. and under 65		10	18	36	73	142			
65 mg. and under 75			16	31	63	122			
75 mg. and under 85			14	27	55	106			
85 mg. and under 95			12	24	48	95			
95 mg. to 100 incl.			11	22	44	85	170		
200 mg.				11	22	43	86	172	
300 mg.					14	28	56	112	
400 mg.					11	22	44	88	172
500 mg.					8	17	34	68	136
600 mg.						14	28	56	112
Minimum weights of lead, lbs.	0.5	0.75	3.25	9.25	9.5	36	58.5	91	135

[a]These figures provide adequate protection to undeveloped photographic film under conditions of shipment provided by the express companies. Radium cannot be sent through the United States mail.

C. PROTECTION FROM X-RAYS

1. *Special Features*

Although the problem of protecting personnel from x-radiation is similar in many respects to that of protecting them from gamma rays, actual conditions frequently are very different. Physiological effects to be expected are much the same in kind, though not always in degree, and the tolerance dosages measured in terms of ionization are the same. Since the intensities and wave lengths of the radiations differ considerably in many applications from those encountered in the use of gamma rays, the details of protective arrangements must be modified to correspond.

The source of x-rays, the x-ray tube, because of its more extensive volume and the necessity of providing electrical conductors, increases the difficulties of adequate shielding. Such a bulky source also scatters diffuse radiation in the vicinity, an effect that is the more pronounced because of the much higher intensities of radiation commonly used. In dealing with the protection of personnel engaged in this work, the electrical hazard from the high potentials also must be discussed since this is about as frequent a source of injury as exposure to the radiation.

2. Protection from Electric Shock

For industrial applications of x-rays, this problem can be divided into two general cases depending on the two types of generating equipment ordinarily used. One is the portable or semiportable unit in which all parts are built into a single enclosure and shielded electrically. In the use of this unit, the operator cannot take advantage of the electrical protection offered by insulating the surface of floors and surrounding objects. Rubber shoes and gloves may reduce danger of shock to some extent, but the only sure protection from shock is a continuous grounded metal enclosure for all parts of the unit, so that it is quite impossible for the operator to touch any part that is above ground potential. This includes high voltage and low voltage cables, control panels, and all other exterior parts. The electrical bonds between these parts not only must insure permanent electrical union of the parts, but also should be substantial mechanically. In some cases, a single heavy cable connecting some part of the grounded system to a permanently earthed point, such as a water pipe, may be sufficient. However, in some types of equipment, high frequency currents may develop that will cause sparks to ground unless several grounds are used at frequent intervals. This is particularly true of long high-voltage cables. These sparks may be harmless in themselves, but may cause insulation failures that will permit the direct current voltage to break through.

The second type of x-ray generating equipment, which is less common, is built into one or more rooms, requiring all work to be brought to the x-ray tube. The same general rules apply to this type of equipment, but greater precautions must be used where parts cannot be permanently shielded. If the high voltage is generated in a separate room, provision must be made so that it is impossible to enter the room with the generator in operation. If high voltage conductors are not enclosed in grounded shields, they must be at a sufficient distance from all points where personnel may normally walk so that there is no possibility of injury from a spark. This distance is about 7½ feet for voltages below 225 kilovolts and correspondingly greater for higher voltages. Suitable signal lights are recommended to indicate the various conditions of generating equipment, and should be so arranged that they are not readily misinterpreted. In all cases, a pilot light should indicate when the main switch controlling the generator is closed.

Overload circuit breakers of a sensitive and quick-acting type should be included in the primary circuit and adjusted to throw at 20 per cent above normal load.

The control panel of all x-ray generators should be located so that the x-ray tube is completely in view of the operator. This may be accomplished by some type of indirect viewing device to screen the operator from scattered radiation; or a suitable filter, transparent to visible light but sufficiently opaque to x-rays, may be placed in the line of sight.

Since many electrical shocks prove fatal only because of failure to apply restorative treatment at once, it is imperative that all personnel concerned with the operation of an x-ray unit be familiar with the methods of artificial respiration and

the aftertreatment of a revived person. This familiarity should be the result of actual training. Although a physician should be summoned at once, the restorative measures should be started immediately, since the chances of a successful outcome are greatly increased by appropriate procedures in the first few minutes after the shock.

Recently Singer, Wyckoff and Day[5] made a careful series of measurements on the relative thicknesses of lead, concrete, and steel required for protection from a narrow beam of x-rays generated by potentials from 200–1400 kv. They find that for 1400 kv. the ratio of thickness of concrete to the thickness of lead is 5.5, a relation that is strictly linear from 10 to 75 cm. of concrete. At 1000 kv. this ratio is 6.4 through a range of thicknesses of concrete from 10–65 cm., with small departures from linearity in the region of thicknesses of concrete between 10 and 20 cm. At 600 kv. the ratio has increased to 10 for a range of thickness of concrete from 10–50 cm., with only slight departure from linearity. At 200 kv. the ratio is about 50 between 10 and 25 cm. of concrete.

The ratio of the thickness of steel to the thickness of lead is found to vary from about 13.5 for 200 kv. radiation to about 1.5 for 1400 kv. radiation.

3. Shielding Materials for Protection against X-Rays

For many purposes, lead is most suitable for use in screening x-rays. In some situations, however, it is more convenient and economical to use other materials, including the structural materials of the building itself. One of the most common is concrete, carefully compounded and poured to prevent formation of air spaces. It is usual to specify the lead equivalence of such materials to indicate their relative efficiency as a screen. The protection coefficient, which is the ratio of the thickness of lead to the thickness of material that absorbs a given x-ray beam to the same extent, is more convenient for calculation. The lead equivalent for a material is the thickness of lead found by multiplying a given thickness of the material by its protection coefficient. Values for protection coefficients, taken from the data of Kaye[5a] and his associates, are given in Table 6.

TABLE 6

Protection Coefficients (with Reference to Lead) for Some Common Structural Materials

Building material	X-rays				Gamma rays
	150 kv.	200 kv.	300 kv.	400 kv.	
Iron	0.08	0.07	0.11	0.14	0.47
Concrete	0.13	0.014	0.026	0.033	0.14
Brick	0.009	0.009	0.015	0.019	0.08

[5] G. Singer, H. O. Wyckoff, and F. H. Day, *J. Research Natl. Bur. Standards*, **38**, 665 (1947).

[5a] G. Kaye, W. Binks, and G. E. Bell, *Brit. J. Radiol.*, **11**, 676 (1938).

When dealing with x-radiation generated by potentials above 200 kv., scattering of the radiation is appreciable. At about 500 kv., the scattered radiation has a hardness of about one half that voltage, and for 1000 kv. the value is one third. Therefore, in computing thicknesses of shielding material where scattered radiation may be involved, the absorption for x-ray voltages corresponding to those of the scattered radiation must be used.

4. Shield of the X-Ray Tube

The x-ray tube in all cases should be completely surrounded, except for the opening for the emergent beam, with protective material of adequate thickness to reduce the radiation to the point where no more than 0.1 *r* per 8-hour day can be measured at any position likely to be occupied by personnel. There is a constant trend toward including the protective screen as an integral part of the tube structure, or support. However, it is desirable to make certain that the screening is adequate in all such types of tubes. Table 7 shows minimum lead thicknesses required for shields for a few typical voltages applied to the x-ray tube. For safest

TABLE 7

Lead Thickness Required to Protect Individuals from X-Rays Generated by Various Voltages

X-rays generated by peak voltages not in excess of	Minimum required thickness of lead barrier	X-rays generated by peak voltages not in excess of	Minimum required thickness of lead barrier
75 kv.	1.0 mm.	400 kv.	15.0 mm.
100	1.5	500	22.0
125	2.0	600	34.0
150	2.5		
		800	40.0
175	3.0	1000	80.0
200	4.0	2000	175.0
225	5.0	5000	290.0
300	9.0		

operation, personnel should never remain unnecessarily in the vicinity of an x-ray tube in operation, even though measurements have shown that the shielding meets the usual requirements. In most industrial applications there is no reason for anyone to be near the x-ray tube during an exposure.

5. Screening Complete Rooms

In some situations it is desirable to line with lead or equivalent material a complete room in which an x-ray tube is located in order to provide protection, in adjacent rooms, from the scattered radiation. When this is done, the protective material should be joined in a lapped joint; and all perforations, such as nail holes, should be adequately covered with lead. Lap joints that leave no unobstructed path

for x-rays also should be provided at the doors of such a room. The thickness of this protective material should conform to the figures given in Table 7.

6. *Ventilation*

In x-ray installations where corona discharge may generate noxious gases, such as oxides of nitrogen and ozone, forced ventilation is required. Such a condition exists where high-voltage conductors of small diameter are exposed in the air. Under usual conditions, the rate of change of air ordinarily recommended for general ventilation, 4 or 5 changes per hour, will be sufficient to reduce these gases below the level where any discomfort or harmful exposure will result.

7. *Special Conditions*

It is impossible to suggest, within a reasonable space, rules that will apply to all conditions. At best, illustration of the general principles as applied to average situations can be sketched briefly. Where unusually high voltages are used, or other exceptional features are present, safety can be assured only by careful measurements of exposure at stations occupied by personnel under actual operating conditions. Lead thicknesses given by Kaye[6] for extremely high x-ray voltages are included in Table 7.

8. *Unnecessary Hazards*

Under this title should be considered those uses or misuses of x-radiation that serve no real purpose but to expose individuals unnecessarily to possible injury. It is needless to say that all such procedures should be discouraged. Two examples may be cited to illustrate. In many shoe stores, x-ray machines, under no expert supervision, are occasionally used to permit customers to examine the bones of their feet by means of a fluoroscope after fitting new shoes. Since no limit is set on the duration of such exposures, it is surprising that numerous cases of injury have not come to light. Another illustration occurred recently in a large industrial plant where employees were permitted to use a medical x-ray installation to examine themselves for metal splinters, or make any other use of the machine that struck their fancy. This occasioned an outbreak of severe radiation dermatitis, and possibly other injuries that were not immediately identified by examining physicians. Considerable damage was inflicted before a correct diagnosis led to the cause, and the practice of self-examination was discontinued. The obvious conclusion from all such incidents is that no x-ray machine should be operated by other than a trained technician well aware of the limits of safe exposure and of the consequences of overexposure. Furthermore, the technician should be responsible for the enforcement of adequately safe procedures in all operations involving the use of the x-ray equipment. In no other way can a certain degree of carelessness, either through ignorance or foolhardiness, be prevented.

[6] G. Kaye, *Nature*, **145**, 370 (1940).

III. Infrared and Ultraviolet Radiation

A. INFRARED

1. General Effect

The long wave lengths of infrared (heat) radiation can inflict no deep injuries in the human body, since they are readily absorbed by the surface tissues. Although the full effects to the surface tissues do not develop for several hours, there is after exposure some immediate discomfort in most cases of overexposure. This discomfort gives adequate warning. The eyes, however, may suffer from continual exposures to infrared radiation that is well below the level that causes general discomfort. There is some evidence that this may result in cataract. Although only a small fraction of the energy is absorbed in the lens of the eye, the lens cannot lose heat readily. An additional injury is a permanent heat necrosis of the retina, most likely to occur in unprotected eyes at some distance. Fortunately, in most situations where overexposure of eyes to infrared radiation may occur, visible radiation also is so intense as to require protective goggles.

2. Protective Measures

The effects of excessive heat on bodily comfort and resistance can be reduced somewhat by taking salt tablets and drinking plenty of water to replace evaporational losses by perspiration.

Radiation screens are particularly effective if not placed too close to the individuals protected. Since they absorb radiation readily, they rise in temperature sufficiently to re-emit part of the energy received.

Eyes should be protected, by suitable glasses, from direct radiation arising from areas that give off intense heat, even though the temperature is not necessarily high.

B. ULTRAVIOLET

1. General Effect

Ultraviolet also is readily absorbable in human tissues, so that it produces superficial injuries, chiefly to the skin and eyes. The effects are generally familiar in the form of sunburn, since it is the ultraviolet portion of the sun's spectrum that is chiefly responsible for the erythema. There is a measurable latent period between exposure and the development of the injury. Therefore, exposure sufficient to cause deep burns may be endured without immediate discomfort. The severity of the burn depends on the spectral distribution of the energy in the ultraviolet region, as well as the total intensity. Certain wave lengths are more effective in producing injury than others, as indicated by the curve in Figure 6, which shows the relative effectiveness of various wave lengths in producing an erythemic reaction.

Ultraviolet produces serious disturbances in the eye, which may last for several days and result in great discomfort. Ultraviolet is absorbed in the outer layers of the eye. Practically all radiation below 2950A is absorbed in the cornea and conjunctiva, the amount of absorption falling off from there to 3600A. This absorption of radia-

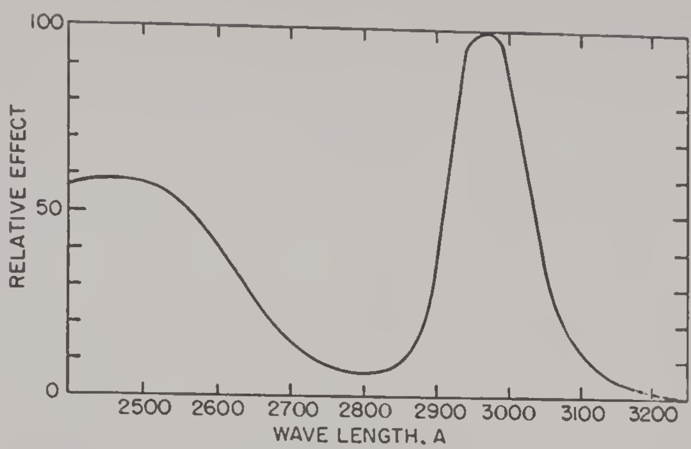


FIG. 6. The relative erythemic effect of ultraviolet rays of various wave lengths.

tion produces conjunctivitis. The symptoms of injury occur 4 to 8 hours after exposure, and may last several days. Great care should be taken to prevent secondary infection. Although the conjunctivitis itself is rarely serious, attempt of the victim to allay the irritation by rubbing the eyes may cause ulceration.

2. Protective Measures

As a result of work done at the National Bureau of Standards by Coblentz[7] and his associates, standard specifications for the transmissive properties of glasses used in goggles are available. These are given, with corresponding shade numbers, in Table 8. The selection of a particular shade number for a given type of work de-

TABLE 8

Specification of Transmissive Properties of Eye-Protective Glasses[a]

Shade No.	Density, D			Per cent transmission		
	Minimum tolerance	Standard value	Maximum tolerance	Maximum tolerance	Standard value	Minimum tolerance
2	0.22	0.429	0.63	60.3	37.3	23.0
3	0.64	0.857	1.06	22.9	13.9	8.6
4	1.07	1.286	1.49	8.5	5.18	3.3
5	1.50	1.714	1.92	3.2	1.93	1.2
6	1.93	2.143	2.35	1.18	0.72	0.45
7	2.36	2.571	2.78	0.44	0.27	0.166
8	2.79	3.000	3.21	1.62	0.10	0.062
9	3.22	3.429	3.63	0.060	0.037	0.0230
10	3.64	3.857	4.06	0.0229	0.0139	0.0087
11	4.07	4.286	4.49	0.0085	0.0052	0.0033
12	4.50	4.714	4.92	0.0032	0.0019	0.0012
13	4.93	5.143	5.35	0.00118	0.00072	0.00045
14	5.36	5.571	5.78	0.00044	0.00027	0.00017
15	5.79	6.000	6.21	0.00016	0.00010	0.00006

[a]Based on the formula, $D = 3/7$ (Shade No. 1) $= \log$ (100/transmission), and on the maximum and minimum tolerances, ± 0.21 on density value. The corresponding transmissions are given to the nearest round number.

[7] W. W. Coblentz and R. Stair, *J. Optical Soc. Am.*, **20**, 624 (1930).

pends on several factors and must, to some extent, be left to the individual preference of the worker. The amount of light should be reduced to the point where it is possible for the worker to see the work clearly without discomfort.

A frequent by-product of the required use of goggles for protection of eyes is a spread of eye infections from exchange of goggles among workers. It is therefore important that workers have their own visual protective equipment, which must be sterilized at intervals.

It should be noted that welders, for example, are often exposed to radiation from near-by welding, from which they must be protected. Another frequent occurrence is eye injury from ultraviolet incurred by onlookers or workmen not actually engaged in welding, since ordinarily they wear no protective goggles. Accidents of this kind can be greatly reduced by providing opaque inclosures for operations where ultraviolet radiation is involved. Where possible, these should be permanent, since portable screens and partitions may not always be adjusted to give complete protection.

3. Tolerance

The Council on Physical Therapy of the American Medical Association has suggested[8] that individuals should not be exposed to intensities of ultraviolet greater than 0.5 microwatt per square centimeter during a 7-hour period, nor more than 0.1 microwatt per square centimeter for a continuous 24-hour day. A convenient device for field measurement of ultraviolet exposures is described by Andrews.[9]

IV. Corpuscular Radiation

Under this heading may be grouped alpha particles, beta particles, protons, and neutrons. Alpha particles have very low penetrating power so that sources of this type of radiation external to the body can produce very little biological effect. They are stopped by a few inches of air. They do represent a serious source of injury when the source is within the body, a subject discussed in the section on poisoning from radium, thorium, or other substances emitting alpha particles.

The beta rays from radium, and from many artificially radioactive isotopes, have a much greater penetrating power than do alpha particles, in some cases being able to traverse a considerable fraction of an inch of animal tissue. Therefore, where strong sources are handled, screening must be used. Fortunately, approximately one-eighth inch of lead, iron, or brass will absorb most radiation of this type completely. An equivalent amount of glass in weight per square inch is likewise effective. Overexposure to beta rays will produce effects on the skin and adjacent tissue. Serious burns can result from this type of overexposure, particularly on the hands.

NEUTRONS

1. Types and Effects

The anticipated development of sources of nuclear energy for industrial applications will give considerable importance to the problem of protecting industrial

[8] *J. Am. Med. Assoc.*, **122**, 503 (1943).

[9] H. L. Andrews, *Rev. Sci. Instruments*, **16**, 253 (1945).

workers from neutron radiation, a subject which heretofore has been of interest only to a relatively small number of persons engaged in research in this field.

The neutron is a particle of approximately the mass of a hydrogen nucleus but without electric charge. Therefore it does not ionize atoms directly to any important extent. However, secondary products of its reaction with matter do produce ionization, and are therefore biologically dangerous. There are a variety of ways in which these secondary effects are produced, but for practical purposes we may divide neutron radiation into two general classes characterized by the speed with which the neutrons are moving. Those that move with a speed corresponding to that of the thermal agitation of molecules, at a given temperature, are classed as slow or thermal neutrons. Those that move at greater speeds are classed as fast neutrons, and may have energies up to several million electron volts, whereas the thermal neutrons have energies of approximately 0.03-electron volt.

The effects of these two classes of neutron radiation are quite different in relation to biological hazards. When tissue is irradiated by fast neutrons, the biological effects are predominantly due to the secondary radiation. These neutrons on collision with the hydrogen atoms in the tissue give them a considerable portion of their energy. These hydrogen atoms thus become protons and, having a positive charge, they are capable of producing strong ionization. Since from the nature of the process these protons are produced in all depths of tissue, they can produce injury in all parts of it.

2. *Measurement*

The measurement of the intensity of fast neutrons must be based on the information in the preceding paragraph. Since the neutrons do not ionize directly, the ionization chamber, or other detector, must have walls composed of material containing hydrogen atoms, or be surrounded with such material in such a way that the protons can enter the effective volume of the detector and produce ionization. For example, the Victoreen minometer equipped with a 100-*r* chamber will satisfy this requirement since the bakelite wall contains hydrogen. It would be preferable for biological purposes to replace the bakelite with a substance containing the same concentration of hydrogen as living tissue. However, this discrepancy can be taken account of in the specification of the tolerance exposure. It has become conventional to designate a reading on an instrument of this kind as 1 *r* when the meter gives the same indication in the beam of fast neutrons that it does for 1 *r* of gamma radiation. However, it can be estimated that the biological effect of the neutron beam will be nearly three times as great as that produced by 1 *r* of gamma radiation, from the consideration of the recoil protons alone. Experiment has shown that this factor may vary from 2 to 10. Therefore, it has been the practice to set the tolerance for fast neutrons at 0.01 *r*, when *r* is defined as on page 241, for an 8-hour day.

Contrasted with fast neutrons, which have a high degree of penetration in matter, slow neutrons are very quickly absorbed in matter. This absorption is in the nature of a nuclear combination of the neutron with the atoms, resulting in the

production of new types of atoms and the liberation of gamma and beta rays. This absorption occurs in the first few centimeters of animal tissue. Under these circumstances the surface layers of the body are converted into an artificial source of radiation in which gamma rays predominate. Therefore, the biological effects to be expected can be determined by means of any device for measurement of gamma rays located close to the body. The Victoreen "fountain-pen" type of chamber worn on the person should provide a reliable guide to this type of exposure.

In those situations, occurring frequently in practice, where both slow and fast neutrons may be present, as well as gamma radiation, it is important to control exposures in terms of all three. Since slow neutrons and gamma rays contribute to one general effect, which can be measured in terms of the gamma radiation in roentgens, this means that in addition the intensities of the fast neutrons must be measured. In general, conditions should be arranged so that the combined intensity is always well below the tolerance level, so that measurements made in a general survey are needed only to confirm that such a situation exists. Monitoring stations of continuous recording, or integrating instruments located at strategic points, will then indicate whether safe conditions are maintained. Since it is usually relatively easy to insure that the sum of effects from all three radiations, fast neutrons, slow neutrons, and gamma rays, is below the tolerance level for any one, a measuring device that responds to both gamma rays and fast neutrons may be used. Any ionization chamber with walls containing hydrogen satisfies this requirement, after suitable calibration.

3. Shielding

The shields for stopping the two types of neutrons, swift and slow, are as different as their properties would indicate. Since swift neutrons are reduced in energy and finally stopped only by direct collision, most effectively with hydrogen atoms, the shield must contain hydrogen atoms. Water or paraffin is effective and must be used in thicknesses up to several feet, depending on the initial energy of the neutrons. For neutrons of thermal energy, cadmium or boron is quite opaque, so that thicknesses of approximately 1 or 2 mm. of metallic cadmium are sufficient. Gamma rays are generated in the process of capture of these neutrons, however. Consequently, for strong neutron radiation an additional layer of lead or other material must be added to absorb the gamma rays on the side of the emergent radiation.

V. Poisoning from Radium or Thorium

A. RADIUM POISONING

1. Historical Summary

Radium poisoning as a definite source of injury was first brought to light in this country by a report, in 1924, by Blum, a New York dentist, who encountered a case of chronic osteomyelitis in the mandible of a girl engaged in applying radioactive paint. Without any knowledge of the kind of material with which this girl worked,

he concluded that the nature of the affliction was so unusual that it must result from some type of occupational poisoning, and published a statement to this effect.[10]

In the following year, Hoffman,[11] who was asked to investigate the plant in New Jersey where girls were employed to apply radioactive paint, found from an examination of death certificates of deceased former employees that these certificates were strikingly similar, although made out by different family physicians, who were entirely ignorant of the true cause of death.

There was frequent mention of jaw necrosis, anemia, and buccal lesions, although the immediate cause of death was usually given as some well-known disease that exhibits some of these symptoms. It was highly improbable, in Hoffman's opinion, that this could be accidental. After he had assembled data on five deaths and twelve living cases, where infected jaws and anemia were predominant features, he concluded that they represented a new type of occupational poisoning, since all cases had worked at the same plant. From his investigations of the working conditions and the nature of the material applied by these workers, he also formed the opinion that the mesothorium in the paint had something to do with the symptoms observed. This opinion was further confirmed in his mind by the observation that after dipping their brushes in radioactive paint the girls habitually pointed them between their lips. This practice would give an excellent opportunity for ingestion of the paint.

These preliminary reports led to a series of investigations, sometimes with contradictory conclusions. In most of these investigations, the radioactive component of the paint was ignored and some other source of the disease was sought. However, in the same year Martland[12] examined two girls who were suffering from extensive jaw necrosis and anemia. Both girls died and, as a result of autopsies which he performed, and investigations on living patients suffering from the same symptoms and engaged in the same work, he was able to formulate an extensive report which clearly, for the first time, traced the disease to its true origin.[13] From an examination of expired air, he was able to detect the presence of radon by the large number of alpha particles revealed by a zinc sulfide screen in a darkened room when the subject breathed against it. From the skeletons, after death, he proved the presence of radioactive material in the bones by electroscopic and photographic tests. By chemical extraction methods he recovered 150 micrograms of radium from one skeleton. At the same time, from examination of patients suffering with the disease, he was able to describe more accurately the type of anemia, and the nature and progress of the bone lesions. In this way, he accumulated information that would provide easy means of identification of the disease from the symptoms. As a result of this clarification of the picture, it became evident that deaths of workers as early as at least 1922 had been the result of radium poisoning, although attributed by family physicians to other diseases.

[10] T. Blum, *Am. Dental Assoc.* (1924).

[11] F. E. Hoffman, *J. Am. Med. Assoc.*, **85**, 961 (1925).

[12] H. S. Martland, P. Conlon, and J. P. Knef, *J. Am. Med. Assoc.*, **85**, 1769 (1925).

[13] H. S. Martland, *J. Am. Med. Assoc.*, **92**, 466, 552 (1929).

It is of interest to consider the general environment under which these tragic circumstances developed, in which undoubtedly more than two score persons lost their lives within a brief span of years, and many others were afflicted with crippling injuries that undoubtedly brought on death at an untimely age. In the period of World War I and immediately thereafter, about 800 girls, at one time or another, were employed in one plant in New Jersey painting the dials of clocks and instruments. There was a considerable demand for such articles for military use and, in the expansion of the industry, workers were recruited from other types of employment where similar skills were required. They usually were paid in accordance with the number of articles they completed per day, and were not specifically warned of any particular hazard, since the dangers from the ingestion of radium were not then understood. Consequently, they adopted procedures that would enable them to produce acceptable work at the most rapid rate. Many of these workers had applied other types of paint, in previous employment, which were not sufficiently toxic to produce any ill effects if the fine brushes were pointed by means of the lips. They soon discovered that this was a very effective procedure in radium dial painting. Since the paint consisted chiefly of zinc sulfide suspended in a water solution of gum arabic, occasionally thinned with water to give proper working consistency, there was no natural deterrent to the procedure. The amount of radium that a worker might ingest under these circumstances has been estimated at from 15 to 200 micrograms per week. This explains in a few words how the situation developed. Early in the investigation, the employers sensed that radium poisoning might be the cause of the deaths and injuries, which were rapidly mounting, and ordered the practice of tipping brushes between the lips discontinued. However, such a regulation was difficult to enforce, and it was not until the advent of plastic adhesives with organic solvents of disagreeable taste and odor that this practice was entirely eliminated.

Although it is now well established that the practice of pointing the brushes with the lips was the predominant cause of the injury suffered by these workers, there are alive today, in apparent good health, several workers who used this method of pointing brushes for several years. This fact is mentioned to show that parts of the confusion in arriving at a solution of the problem arose from individual differences in the workers. Those who survived apparently developed a method of pointing the brushes that did not result in ingestion of appreciable amounts of the paint; others were more careless in this respect.

2. *Radioactive Nature of Radium*

Radium is always accompanied by its decay products in amounts dependent on a number of conditions. The properties of a sample of radium will be more readily understood by reference to Figure 7, which shows the genetic relationships in the radium family. We see that the immediate product of radium is a gas, radon, which decays to half-value every 4 days. This transformation is accompanied by the emission of an alpha particle for each atom transferred. By emission of another

alpha particle, radon becomes RaA, which in the same way transforms into RaB. RaB changes into RaC by emitting a beta particle. Here, a branching occurs that reunites in RaD, which by emitting a beta particle becomes RaE. RaE in the same way transforms into RaF. By emitting an alpha particle, RaF (polonium) becomes RaG, an inactive isotope of lead. The crosshatched circles represent elements that emit the more powerful gamma ray, associated with radium. Therefore, we can see

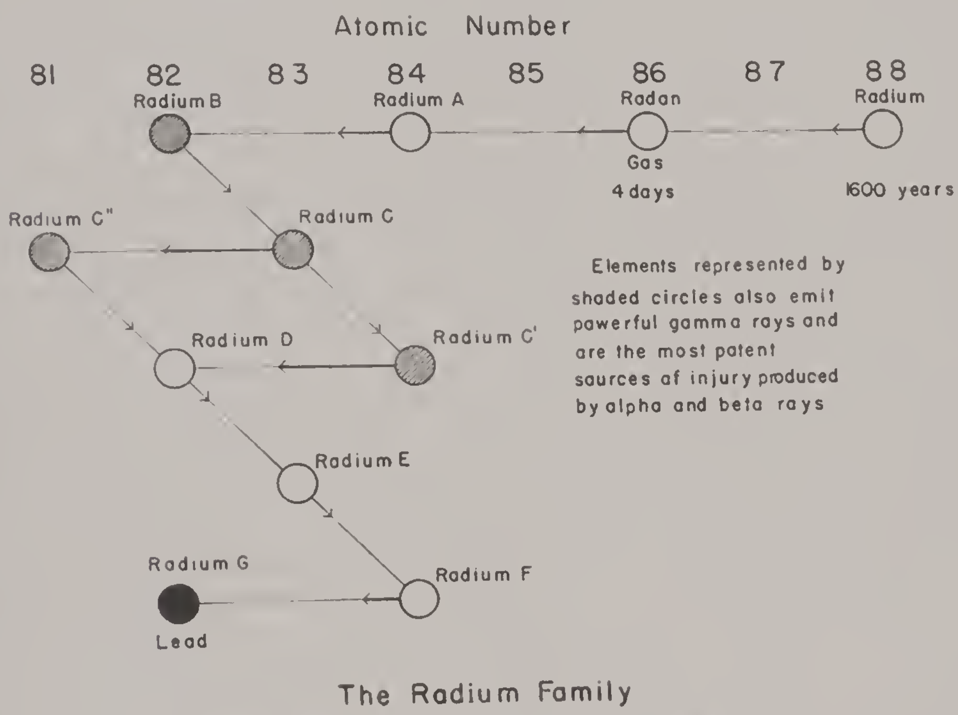


FIG. 7. The genetic relation of various products originating from the transformation of radium. Heavy black arrows painted horizontally to left represent emission of beta rays. Shaded circles represent members that emit strong penetrating gamma rays.

that radon, even after removal from the radium, will have associated with it most of the powerful radiations capable of producing injury. The quantitative relation between the radon generated and the parent radium can also be used to measure the amount of radium present, by measuring the radon produced.

Radium luminous compound. Radioactive luminous compound, as ordinarily used in the radium dial-painting industry, consists of a mixture of phosphorescent zinc sulfide and radium. In some instances mesothorium, a radioactive isotope of radium, is used in place of radium. For economic reasons, the use of mesothorium has been discontinued, so we may confine our discussion to the compound containing radium. It should be noted in passing that the effects of mesothorium are very similar to those of radium, but the methods of detection and measurement are somewhat different.

3. Injuries and Symptoms in Radium Poisoning

The study of the early severe cases of radium poisoning revealed quite definitely that we have here a radiation injury that, although differing in some respects from other known types, is produced basically in the same way. The chief difference from the kinds of exposure already discussed in this chapter lies in the mode in which the dose of radiation is administered to the cell structures, and in the chief ionizing agent responsible. It is now well established that the alpha rays from radium and its products, deposited in the bone, were predominantly responsible for the injuries to the bone structure and to the blood-producing centers of the bone marrow. Although the alpha particles can penetrate only a very thin layer of tissues, they produce a dense column of ions that probably affect most of the cells in their path. With the sources of these alpha rays distributed in the bone tissue itself, it is easy to see how great damage could, and did, result. This situation is aggravated by the further well-established fact that radium, once deposited in the bones, is eliminated very slowly, and no satisfactory therapeutic means for speeding up this elimination have been found.

Some of the more severe effects and symptoms of radium poisoning have been mentioned in the discussion of the history of this hazard. These symptoms are not to be regarded as helpful in future control of radium poisoning, since it is now known that almost all detectable symptoms appear only in late stages of the disease. This is revealed by the apparently contradictory indications encountered in many of the early cases studied. We need recall only a few, such as the development of osteogenic sarcomas, which usually proved fatal in a few months after they were discovered, while at the same time the blood picture remained practically normal. This shows clearly that the blood count cannot be relied upon to guard against the effects of radium poisoning. On the other hand, severe anemias were discovered in some radium dial painters, which, however, refused to yield to treatment, and finally proved fatal. The study of the deviations from normal in the blood counts in these cases contributed to a solution of the real nature of the disease but, even here, offered no protection to the victim. Therefore, it is obvious that physiological symptoms and indicators may appear at a period too late in the progress of the disease to be of any value as a safeguard. When they do appear, they show that the injury has reached a dangerous stage, where the outcome is doubtful. We may conclude that periodic medical examinations of workers in this industry are of value in determining whether they are otherwise in good health, but have little bearing on prevention of radium poisoning. Regular blood counts have a similar significance, and also may serve to detect cases of radium poisoning that have occurred in spite of protective measures. However, the violation of rules of proper procedure must be so flagrant to produce such cases that they ordinarily should be detected by other means long before such a stage of injury could result.

4. Tolerances

Before discussing methods of measuring the amount of radon present in workroom air, or the amounts of radium in a living person, we shall discuss the levels at which it is desirable to hold these quantities to prevent injurious effects.

Expired air. Although we do not have all the information we would like regarding the amount of deposited radium that can be tolerated by a living person, it is fairly well established that as little as 2 micrograms may prove fatal. By available methods to be discussed, the equivalent of 0.1 microgram can be detected reliably. Proceeding on the now generally admitted principle that any radium deposited in the body is too much, we can say that as soon as the amount of fixed radium becomes reliably detectable the limit has been reached, and the worker so affected should be removed from any possibility of increasing this amount of radium. This quantity of deposited radium will produce a radon concentration in the expired air of approximately 10^{-12} curie per liter—a curie being the amount of radon in equilibrium with one gram of radium. Therefore, when measurements reveal a concentration of radon in excess of 10^{-12} curie per liter, this can be accepted as evidence that radium is deposited in the body.

In interpreting the significance of the measurement of radon in expired air, the occupational record of the subject from which the sample was taken must be taken into account. The term "fixed" radium has been used to indicate the radium that is in a slow process of elimination from the body. In the period immediately following ingestion, the radium is eliminated rapidly—approximately 70 per cent in the first 24 hours, and about 95 per cent in a 5-day period. After this, the elimination is very slow. Therefore, if a sample of expired air is taken on a day subsequent to a continuous period of several days of dial painting, part of the radium indicated by the measurement of radon will be eliminated in the next few days and, if no further exposure occurs, in a subsequent measurement a few days later there will be a noticeable decrease in the radon content of the expired air. This decrease is enhanced by the fact that some of the radium indicated by the first measurement was probably not yet deposited in the bone. A larger amount of radon would appear in the lungs from this radium than from radium more or less permanently deposited in the skeleton. Circumstances of this kind have an important bearing on the probable recovery of an individual who has a high radon content in the breath. They also make it evident that detailed occupational records of dial painters should be kept as an aid in interpreting the results obtained from measurements of radon in the breath.

Workroom air. There is definite evidence that radon, when inhaled, can produce injuries such as leucopenia, and possibly lung cancer. When the concentration reaches 10^{-7} curie per liter, anemias can be expected to become clearly evident, the severity depending on the period of exposure. It is also known that when this concentration is reduced to the order of 10^{-9} curie per liter, individuals suffering from leucopenia will recover.[14] Therefore, tolerances for workroom air have been vari-

[14] J. Read and J. C. Mottran, *Brit. J. Radiol.*, **12**, 54 (1939).

oulsy set at 10^{-10} to 10^{-11} curie per liter. In most dial-painting plants, the lower limit is readily obtainable by adequate ventilation in conjunction with other usual protective measures. In view of the fact that even the higher concentration is, so far as is definitely known at present, presumably safe, it is at the present time a matter of judgment as to which limit should be enforced.

5. *Detection of Unsafe Conditions*

Radiation as an indicator. With the failure of physiological symptoms as a guide in detecting incipient exposure to radium poisoning, the question arises as to what means are available to reveal conditions that may result in injury early enough to guard against such possibility. Inasmuch as radium and radon are the sources of radiation that produce the injury, it is natural to look to some method that will detect their presence at points where injury may be produced. Fortunately, the powerful ionizing effects that produce the biological changes also offer a ready means for revealing their presence quantitatively. It is necessary only to establish some order of tolerance to the amount of radioactive material that may be present, to set up a procedure for detecting unsafe conditions long before the appearance of any detectable physiological changes in the worker. Although such a procedure may not in all ways represent an ideal, it is far in advance of any other now available, and we can say at present that it will prevent all but the very minor damages, if followed correctly in all details. In using the radiations from radioactive elements in detecting unsafe conditions, certain precautions must be taken to assure that the radiation measured arises from a location where it may cause injury. For this reason, methods of detecting radium in living persons that depend upon measurements of gamma radiation, such as gamma-ray electroscopes and Geiger-Müller counters, are open to the objection that sources of gamma radiation external to the body may contribute to the measurement. If the subject under investigation happens to have radioactive material on the skin, or in the hair, this material also will be measured and thus lead to a false result. This difficulty is encountered to an even greater extent in any attempt to test the air of workrooms by gamma-ray methods. Therefore, methods that involve measurements of radon by means of alpha radiation will lead to more reliable results from the standpoint of interpretation. Where desirable, these measurements can be evaluated in terms of the radium that produced the radon.

Methods of radon measurement. Sampling methods. Flasks. In the early investigations, measurements of radon concentrations were made with portable ionization chambers connected to gold-leaf electroscopes. With considerable care, such equipment will yield satisfactory results, particularly where the amounts of radon to be measured are relatively large. For the determination of the order of 10^{-13} curie, required for detection of slight increases in the radon concentration in expired air, such methods are not generally reliable. Therefore, such measurements must be made in specially equipped laboratories by experienced technicians. This requires that the sample of expired air be sent to such laboratories in suitable flasks. This procedure has an additional advantage in that measurements made in one laboratory

by the same technicians are more likely to be directly comparable than are those made by a number of observers with portable equipment.

Laboratory measurements of samples of air containing radon are based on a comparison between the radon in the sample and a standard quantity of radon, of similar magnitude. The standard quantity of radon is obtained from a standard solution of radium carefully prepared for this purpose. By knowing the rate of accumulation of radon in such a solution, various known quantities of radon can be obtained from such a solution, up to the equilibrium amount, by allowing the radon to accumulate over various measured periods of time.

The comparisons may be carried out by several methods, but in each the ionization produced in an ionization chamber, by the alpha particles, is the effect customarily used. The number of alpha particles produced in an hour is proportional to the quantity of radon. This number may be determined by direct counting, or by measuring with a sensitive electrometer the total current produced—which is indirectly a method of determining the number of alpha particles per hour.

In addition to being dependent on the properties of the equipment used, the accuracy of all such measurements is dependent on the statistical laws governing the evaluation of random events, since alpha particles are emitted from a radioactive element at a purely random rate. This means that a sufficient number of particles must contribute to a measurement to reduce the standard deviation to the required percentage of the total number observed. Whether this condition is properly fulfilled is most conveniently determined in a method in which the alpha particles are counted directly. The counting method offers other advantages that make it more convenient in use.

A schematic diagram showing the method[15, 16] of using an electrometer for comparing radon samples is shown in Figure 8. A double ionization chamber with the collecting voltages of the two chambers opposed is used, as shown, to neutralize the effects of external sources of radiation. The radon is introduced into one of the chambers, as indicated. To make this equipment automatic, the calibrating switch is actuated by a synchronous motor so that the arm contacts point 1, 2, 3, and 4 in succession once each hour, and the position of the fiber is recorded by means of a special camera. The switch impresses a positive and an equal negative calibrating voltage, and a ground potential on the fiber, and finally connects the fiber in a charged position to the ion-collecting system of the ionization chambers, where it remains during the subsequent hour to record the loss of potential due to the net ionization current produced by the radon in the lower chamber. Provision is made to introduce into the radon chamber either a standard quantity of radon for calibration, or the unknown sample. This method requires very steady voltages on the knife-edges of the electrometer and the ionization chambers, as well as the best quality of insulation for the electrometer fiber and ion-collecting system. For changes made in the sensitivity of the electrometer, measurements must also be

[15] W. D. Urry and C. S. Piggot, *Am. J. Sci.*, **239**, 633 (1941).
[16] R. D. Evans, *Rev. Sci. Instruments*, **6**, 99 (1935).

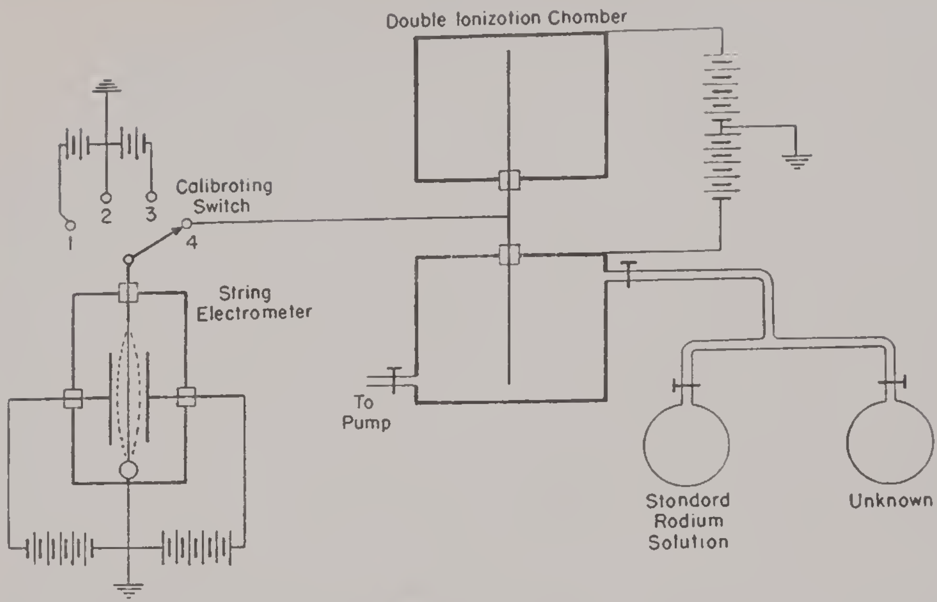


FIG. 8. Schematic diagram of essential elements of equipment for measuring samples of radon by the use of a string electrometer to measure the ionization current produced by the alpha rays from radon in an ionization chamber.

corrected for changes in the capacity of the collecting system. The sensitivity must be adjusted for each sample that differs appreciably from the preceding one. The photographic film or paper must be processed and evaluated before the results can be computed.

A similar schematic diagram is shown in Figure 9, for comparing quantities of radon by counting the alpha particles.[17] Since the individual particles are enumerated and external sources cannot, in general, produce current pulses similar to those that result from the passage of an alpha particle through a gas, only one chamber is required for this method, shown at *I* in the figure. It consists simply of a cylinder of about 4 liters capacity with a central insulated electrode extending along the axis. When a voltage is applied to the cylinder the collecting rod experiences a sudden rise in potential as the ions generated by each alpha particle are collected. To make this voltage pulse sufficiently short in duration for proper amplification and counting, pure nitrogen must be used in the ion-counting chamber. To provide for this, the radon sample, whether from the standard solution of radium, *S*, or an unknown air sample, is passed through a tube, *C*, containing reduced copper heated in a furnace to approximately 500° C. Moisture is removed by the drying bulbs, B_1 and B_2, after which the sample, consisting now of pure dry nitrogen plus the radon, passes into the evacuated chamber, *I*. Sufficient nitrogen is added through the system to bring the pressure in the chamber equal to that of the atmosphere. A sample of air containing radon can be prepared similarly by attaching the flask at (2) or (3)

[17] L. F. Curtiss and F. J. Davis, *J. Research Natl. Bur. Standards*, *31*, 181 (1943).

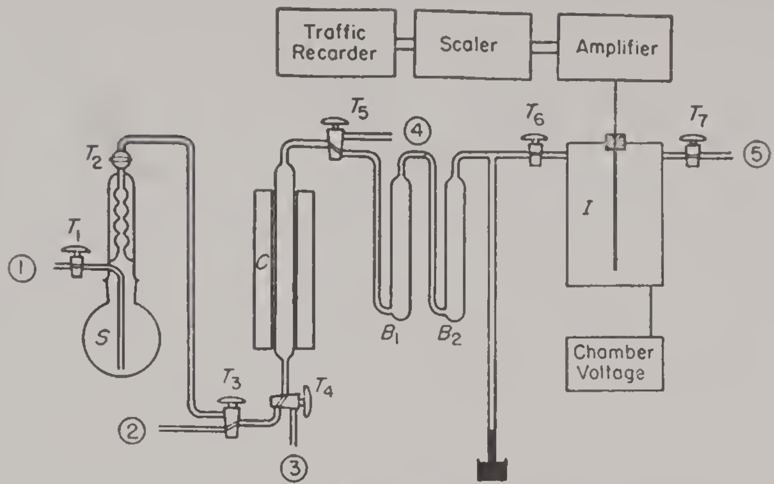


FIG. 9. Diagram of purifying system and apparatus to count the alpha particles from a sample of radon in an atmosphere of pure nitrogen.

and flushing it by a stream of nitrogen through the system into the connecting chamber.

To count and record the alpha particles, the voltage pulse produced by each particle is amplified by the vacuum-tube amplifier sufficiently to operate a scaling circuit that transmits every eighth pulse to the counting mechanism of a commercial recorder designed for counting vehicles passing along a thoroughfare. These machines print, on a moving strip of adding machine paper, the total accumulated count with the hour of the day and the day of the week. This record is immediately available at the end of the period of observation and can be evaluated by a few simple calculations. The advantages of the counting method are: (*1*) no photographic process is involved; (*2*) moderate quality of insulation is sufficient; (*3*) no adjustment is required for various sizes of samples over a wide range; (*4*) the potentials used need not be accurately known, nor constant from day to day; (*5*) the number of events contributing to the measurement is immediately available for evaluating the statistical accuracy of the measurements. Although a considerable amount of electronic equipment is needed, it is all used in circuits that are readily maintained and that require little care beyond replacement of vacuum tubes as they become worn out.

A convenient form of flask for taking samples of air containing radon is shown in Figure 10. It is provided with a central tube, projecting from the special stopcock, through which nitrogen is passed to flush the sample into the measuring chamber. Flasks may be used to take samples of workroom air, or of expired breath. They are usually sent out evacuated so that a sample of workroom air may be obtained merely by opening the stopcock at the place where sampling is desired. To take expired air samples the exhalation is accumulated in some type of gas bag (a basketball bladder is adequate), which is then attached to the flask and the stopcock opened.

In using such sampling flasks, a few simple precautions must be observed. An

expired breath sample should be taken only after the worker has been out of the plant for at least 4 hours. Direct experiments show that the air in the lungs has lost most of the radon acquired from the room air in from 3 to 4 hours. It should be arranged that alveolar air is taken in the sample as far as is practicable. Also, it is very important that the sample be taken where the atmosphere contains no radon contamination, preferably in the open. Otherwise, the subject should be in the room where the sample of breath is taken for about an hour before the sampling is made, and a sample of room air should be taken as a control. As regards room samples, it is important to exclude radium-bearing dust from the flask. Since most workroom air contains such dust, a simple filter is recommended.

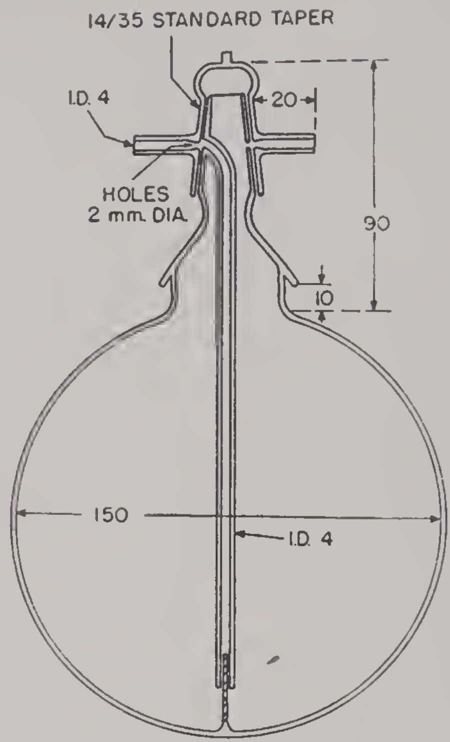


FIG. 10. Cross section of a Pyrex glass flask suitable for taking samples of room air or of breath of workers for determinations of radon content. All dimensions are in millimeters.

6. Protective Rules for Radium Dial Painting

Basis of regulations. The suggestions for regulations and procedures given below are abridged from Handbook No. 27 of the National Bureau of Standards, *Safe Handling of Radioactive Luminous Compound.*

Fundamentally, protective rules for radium dial painting should aim at the prevention of ingestion or inhalation of the radioactive compound during its manipulation. All evidence available at present indicates that this precaution will prevent any serious injury from the radioactive constituents. To secure this result, a generally safe and clean environment must be provided for the worker, and his full co-operation must be enlisted in the observance of a few simple rules, which impose but slight restrictions on the output and production of acceptable work.

Gamma-ray hazards. Since the quantity of radium in radioactive luminous compounds is relatively small, it is only in larger plants, employing 25 or more dial painters, that there is likelihood of a serious exposure to gamma radiation. In all situations where such exposure may be excessive, the precautions discussed in the sections dealing with gamma rays (page 245) should be observed.

Selection of personnel. It is obvious that the problem of safeguarding the health of a dial painter is greatly simplified if only normally healthy individuals are employed. Moreover, persons with certain types of afflictions and diseases may be more susceptible than others to the hazards of this industry. It is also important to make certain that an applicant is not already suffering from exposure to unsatisfactory

conditions in previous employment as a dial painter. Therefore, it is to the best interests of all concerned to require a rigid medical examination, including blood count, of all prospective workers. In particular, those already suffering from anemia, leucopenia, or showing symptoms of tuberculosis, should be rejected. In addition, the expired air should be tested for radioactivity. If this exceeds the tolerance of 10^{-12} curie per liter, the applicant should not be employed.

General procedures. Emphasis should be placed on neatness and cleanliness in all stages of the work. Carelessness in handling radioactive compounds cannot be condoned. A careless worker exposes other workers to risks unnecessarily, as well as himself. Great care should be taken to see that any compound accidentally spilled is cleaned up and disposed of in a thoroughly safe manner. Workers should keep their hands, hair, and clothing free of the compound. No food, or refreshments of any kind, should be consumed in the workroom.

Brushes. The most satisfactory method for applying radium paint seems to be by the use of a small brush. Since tipping of brushes by the lips led to many of the early fatalities, this procedure must be kept under careful scrutiny. Fortunately, the adhesives currently used require organic solvents of unpleasant odor and taste, thus reducing the tendency to point brushes with the lips. The use of bare fingers for this purpose is dangerous, also. The most satisfactory procedure for wiping and pointing brushes entails the use of small squares of cleaning tissue, which are discarded immediately after use into containers reserved for this purpose.

All such discarded material containing radioactive compounds must be carefully collected and disposed of in such a way as not to constitute a hazard. In larger plants, it is frequently returned to the manufacturer of the compound, for recovery of the radium.

Supervision. One of the best safeguards that can be provided for the protection of dial painters is a thoroughly experienced supervisor, familiar not only with the manufacturing process, but also with the points at which hazards may develop. In spite of instructions, employees are frequently tempted to devise methods and procedures of their own, which may not be safe. It should be the duty of the supervisor to detect and prevent the continuance of any unsafe practices. Routine inspections of employees for neatness and the presence of radioactive compound, using ultraviolet light in a darkened room, should be carried out by the supervisor. It is sometimes also convenient to use a source of ultraviolet of moderate intensity to inspect floors and workplaces for contamination by radium luminous compound. Unless the rooms can be completely darkened, such inspections must be made at night.

Equipment. The utensils and equipment used by each dial painter must be kept neat, and should always be arranged in a definite and orderly manner, convenient for the type of work in progress. No untidiness involving radioactive material can be tolerated. The number of utensils and tools on each table should be reduced to the minimum required for the work, and no articles extraneous to the work should be permitted on worktables at any time. This refers especially to

personal effects of the worker, including purses, clothing, cosmetics, and so forth. It is important that the surfaces of all tables on which radioactive compound is handled be smooth and impervious to solvents used for the adhesive. Likewise, smooth floors that can be mopped readily should be provided. Dry sweeping should be prohibited.

Storage and drying of completed work. Painted articles should be removed from the vicinity of the worktable frequently, to prevent any considerable accumulation. If these articles are placed in drying racks, such racks should be enclosed and provided with sufficient mechanical exhaust ventilation, at an exit port, to maintain an inflow of air of at least 75 linear feet per minute at all other ports and all cracks when the cabinet is closed. Cabinets containing 500 or more dials should be located at least 3 feet distant from any worker's permanent station. Finished dials may be stored on open shelves, if in a physically separated room supplied with ventilation not less than 400 c.f.m. per 1000 dials. Since dials in racks and cabinets may be a source of overexposure to gamma radiation, the gamma-ray exposure in the vicinity should be checked by suitable instruments, and workmen should spend only a minimum of time in or near storage areas.

Ventilation. Any operations that produce radioactive dust, such as grinding or scraping of surfaces where luminous compound has been applied, should be avoided as far as possible. Where such procedures are necessary, the operator should be protected by suitably designed exhaust ventilation.

In rooms without forced ventilation, where any considerable amount of radioactive compound is applied, the radon concentration in the air will soon exceed permissible amounts. Therefore, a system of forced ventilation is essential. At present this ventilation is accomplished in two ways: in some plants, general room ventilation is depended upon to remove radon; and in others, individual hoods are placed over each worktable. A combination of the two is preferred. The adhesives used in paints dry quickly and therefore hood ventilation is limited, in that only a moderate current of air can be permitted, or the paints become unworkable. It therefore may not be practical to exhaust enough air through the hoods to provide general room ventilation to sufficiently dilute the radon arising from sources outside the hoods. Ten air changes per hour combined with good housekeeping have been found to provide satisfactory general ventilation to supplement the individual hoods.

Hoods for painting should be enclosed on all sides except the face, which should have an area of approximately 1 sq. ft. The glass top should extend to the front edge with no cutout area. Sufficient air should be exhausted from the hood to maintain an inward flow of air of 50 to 60 l.f.m. at the face of the hood.

Enclosures for the compounding of radioactive paints should be exhausted at a face velocity of not less than 100 l.f.m. Compounding should be done only by a qualified careful workman, cognizant of the hazards involved.

It is obviously necessary that all ventilation herein described should deliver the exhausted air to the exterior, and preferably above the roof. The air should not be recirculated.

It must be pointed out that the real criterion in judging the performance of the ventilation system is provided by measurements of radon concentration in the air in the breathing zones of the workmen. Any system that keeps this concentration below the tolerance level throughout the plant is adequate from the standpoint of the radioactive injuries from radon.

It is necessary to see that ventilating systems are in operation at least a half hour before workers start the day's work, in rooms where radioactive compounds are manipulated. This precaution is required to reduce the radon concentration in the air, resulting from an accumulation during the night in stagnant air. Radioactivity tests should be made occasionally of room-air samples taken at the start of work to test the effectiveness of this ventilation.

Repainting dials. Repainting of radium luminous figures on dials must be done with caution, since the old compound contains essentially all the radium it had originally. Therefore, the old luminous compound, which in practice frequently is removed in the dry state, must not be handled in a way that will permit ingestion, or inhalation, or later become a source of injury through improper methods of disposal. A hood with appropriate ventilation is required for this work. Smooth surfaces are required for parts used to receive the compound that is chipped off, so that it may be removed readily and completely for disposal.

Dressing rooms. In radium dial-painting plants there is absolute necessity for dressing rooms entirely separate from workrooms, where workers may change from street clothes to working costume. It is desirable that workers be provided with smocks and caps, which they never take from the plant. Laundering of these should be arranged for by the employers. These smocks should be the external garment worn at work. A double locker system should be installed, and street clothing kept entirely separate from smocks and caps used at work. All personal effects of the workers should be kept in the dressing room.

B. THORIUM POISONING

1. Industrial Use of Thorium

In addition to the former use of mesothorium in radioactive luminous compound, thorium itself is used in the manufacture of gas mantles, which are still in considerable demand in this country, mainly for use in portable gasoline lights and similar lighting devices. In the extraction of the thorium from the ore, the mesothorium is separated and, usually, refined. The supply of mesothorium is not sufficient in quantity, nor is the regularity of production ample, to permit it to compete with radium for industrial use. Consequently, there is little demand for this radioactive material. The present low cost of radium is an added factor in this tendency. Therefore, the refining of mesothorium in this country is limited to one or two laboratories and a few employees under close supervision. A summary of the hazards and precautions for a laboratory engaged in this work has been published by Schlundt, McGavock, and Brown.[18] These hazards are similar, though in a somewhat in-

[18] H. Schlundt, W. McGavock, Jr., and Mildred Brown, *J. Ind. Hyg.*, **13**, 117 (1931).

tensified degree, to those described in this chapter in connection with the preparation and application of radioactive luminous compound, under the title of "Radium Poisoning."

In the thorium mantle industry the main hazards are probably from thoron inhalation in mantle-soaking operations where the mantles are soaked in open bowls of thorium nitrate solution; and from dust inhalation in the mantle-cutting operation, where considerable thorium-bearing dust is generated. Both operations are readily controllable by local exhaust ventilation. Concentrations up to 4×10^{-9} curie thoron per liter have been found by Evans[19] in this industry, but none of the workmen studied presented evidence of injury, storage, or excretion. The chief difference between this situation and those where materials containing radium are manipulated lies in the methods of measurement of the radioactive gas, thoron, by means of its radiation. The inhalation of thoron or the ingestion of substances containing mesothorium will have the same general consequences as the inhalation of radon or the ingestion of material containing radium.

2. *Tolerances*

The tolerances for exposure to gamma rays from elements of the thorium family, and of exposure to thoron in the air as well as in expired breath of workers, are the same as for radium and radon, given in the preceding sections. The gamma radiation is measured in terms of roentgens and the thoron in terms of curies per liter.

3. *Methods for Measurement of Thoron*

Because the gas thoron has a very much shorter period of existence than has radon, decaying to half value in about 55 seconds, a different procedure must be used to determine the thoron. It is obviously impossible to collect a sample of air and send it to a central laboratory for measurement of the thoron.

One procedure is to measure the thoron at the plant by circulating the air through a system described by Schlundt[18] and his co-workers, and shown in Figure 11. In testing expired air, it is necessary for the subject to breathe continuously into the apparatus during a determination.

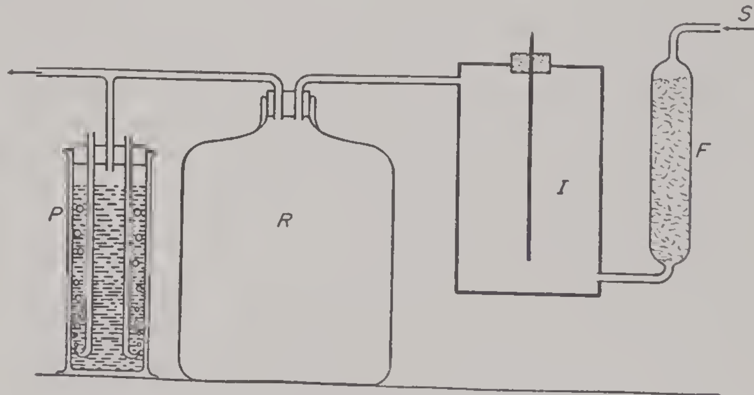


FIG. 11. Diagram of system for measuring thoron content of air by circulating it through an ionization chamber. *P*—constant pressure device, *R*—gas reservoir, *I*—ionization chamber, *F*—filtering and drying tube. *S*—air inlet.

[19] R. D. Evans and C. Goodman, *J. Ind. Hyg. Toxicol.*, 22, 89 (1940).

An alternative procedure, particularly convenient for the testing of workroom air, is described by Evans and Goodman,[19] by which measurements may be made at a central laboratory which can be interpreted in terms of the thoron content of the air in which the sample was taken. The principle of the method rests on the fact that thoron decays rapidly into a solid, thorium A, which has a much briefer existence, decaying in turn to thorium B, which has a half-value period of 10.6 hours. Thorium B is a solid that may be collected on a metal disk, and the disk then sent to a laboratory equipped to measure the alpha rays or the beta rays emitted from the disk. The more powerful ionizing effects of the alpha rays render them more suitable for use in this measurement. To collect the thorium B, an apparatus, which can be made readily portable, is shown diagrammatically in Figure 12. The collector disk, *D*, is

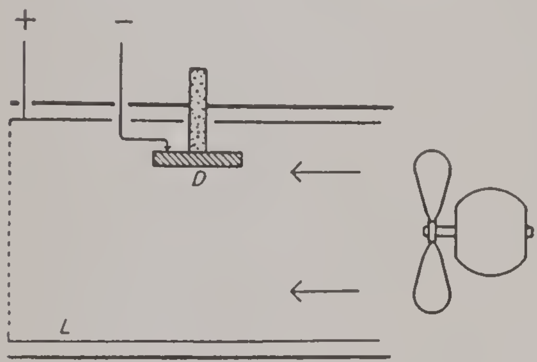


FIG. 12. Diagram of arrangement for accumulating the radioactive deposit from thoron in the atmosphere of a workroom. *D*—disk on which deposit is accumulated, *L*—electrically charged cylinder which creates electric field to drive ThB atoms to *D*.

mounted in a stream of the air to be tested. The disk is held at a high negative potential with respect to the inner surface of the collecting chamber. Since the thorium A and thorium B atoms are present as positive ions they are driven to the collector disk by this arrangement.

4. Protective Rules for Handling Thorium

As has been indicated, the precautions required in handling large quantities of thorium are quite similar to those required in the radium dial-painting industry. These may be briefly summarized as meticulous care in the manipulation of the material to prevent general contamination of the workrooms and equipment, plus adequate ventilation to reduce the thoron concentration to the required level.

If material containing mesothorium in a concentrated form is accumulated as part of the process of refining the thorium, gamma-ray measurements should be made to test compliance with requirements for exposures to this type of radiation.

CHAPTER TEN

Ventilation

W. N. WITHERIDGE

This chapter is devoted and limited to the problems of controlling the quality of indoor atmospheres by one or more of the many forms of ventilation, and will include the methods of restoring indoor air to proper quality for recirculation. The problems of air conditioning for comfort, or the control of temperature, humidity, air motion, and radiation are discussed in Chapter Five, "Environmental Factors in Fatigue and Competence."

Ventilation is the process of passing air through any space, room, or building for the purpose of diluting undesirable air-borne substances to a safe or acceptable concentration. The control of oxygen and carbon dioxide for human respiration is not a major concern of ventilation, as will be shown later.

Ventilation is one of the functions of complete air conditioning, because contemporary physical and chemical air-conditioning processes fail in some degree to restore the indoor air to its "unused" or outdoor condition. The present status of air cleaning does not permit the engineer to depend wholly upon a completely self-contained or 100 per cent recirculating indoor atmosphere. The modern submarine when submerged is perhaps our nearest approach to a self-contained space for human occupancy, inasmuch as it provides at least a *safe* environment for respiratory purposes, entirely detached from the earth's atmosphere.

The term "ventilation" originally implied that outdoor air would be exchanged for indoor air to improve the chemical, physical, and esthetic properties of the inside atmosphere. However, we now know that in certain areas of some highly industrialized cities, the outdoor air is indeed less desirable than well-conditioned indoor air, and the simple process of replacing room air will not create an acceptable environment in all cases. Furthermore, the demand for conserving the energy of heating, cooling, humidifying, and dehumidifying air for indoor use has stimulated the development of highly effective air-cleaning devices. Ventilation therefore is no longer limited to the use of untreated outdoor air.

Most of us are inclined to believe that outdoor air has some property, still undefined, that accounts for its "freshness" in contrast to indoor atmospheres, even

after all known means have been utilized to remove every perceptible contaminant from the indoor air. Undoubtedly, the freedom and exhilaration experienced in the "wide open spaces" is the result of many kinds of stimuli, including sounds, odors, colors, distances, natural and man-made horizons, and complex variations in temperature, humidity, radiation, and air movement. It is definitely unfair to indoor air to compare it directly with the wonderful composite influence upon our five senses that we experience outdoors.

Man has tried in many ways to duplicate the invigorating properties of outdoor air. His methods range in diversity through ozonation, ionization, ultraviolet radiation, perfuming, deodorizing, washing, and thermal adjustment. None of these experiments has solved the problem. However, so long as one is reconciled to the necessity of being indoors, the air conditions provided by the best current air-conditioning practice are eminently satisfactory.

I. Human Ventilation Requirements

Ventilation in residential, commercial, and office spaces is now understood to be necessary in order to control body odors, tobacco smoke, cooking odors, and other odorous impurities for which the human being is responsible, and not in order to supply the required amount of oxygen or remove the carbon dioxide produced by respiration. This is true because the present standard construction of buildings for human occupancy cannot prevent the infiltration and exfiltration of substantial amounts of air, even when all window, door, roof, or mechanical-ventilation openings are closed. Tables 7, 8, and 9 indicate the amounts of outdoor air normally available by natural ventilation or infiltration and provide the rational evidence that suffocation by oxygen deficiency or carbon dioxide excess due to human respiration is virtually impossible in buildings constructed above ground.

In view of the fact that industrial hygienists are called upon to justify this position to those who are not aware of the background of research and experience upon which present ventilation standards are based, a brief review of the effects of respiration on atmospheric air is in order at this point.

A. AIR COMPOSITION

The approximate composition of air under three conditions is given in Table 1. Simple calculations will demonstrate that human beings do not require more than a

TABLE 1

Composition of Air (Volume Per Cent)

Component	Outdoor air dry	Indoor air 70° F. (RH 50)	Expired air 97° F. (RH 100)
Inert gases (nitrogen, argon, etc.)	79.00	78.00	75
Oxygen	20.97	20.69	16
Water vapor	0.00	1.25	5
Carbon dioxide	0.03	0.06	4
Total	100.00	100.00	100

few hundred cubic feet of air per hour to satisfy their demand for oxygen and to dilute to a harmless concentration the carbon dioxide produced. A man, even at heavy work, breathes only about 40 liters (1.4 cu. ft.) of air per minute, consumes about two liters (0.07 cu. ft.) of oxygen, and produces about 1.7 liters (0.06 cu. ft.) of carbon dioxide.

Mackey[1] offers an interesting hypothesis on the physical and chemical changes occurring in indoor air as a result of human occupancy. His analysis is somewhat as follows (several figures in the original statement have been changed following a private communication from C. O. Mackey):

> An adult at rest uses in one minute about 20 cubic inches of oxygen and produces about 18 cubic inches of carbon dioxide. At 70° F., he loses in one hour about 300 Btu of sensible heat and about 0.1 pound of water vapor. Assuming for simplicity that these rates remain constant (which they would not do in fact), if such an adult were confined in an airtight, thermally insulated space of 1000 cubic feet, initially at 70° F. (ignoring humidity), the dry-bulb temperature would increase to 100° F. in less than two hours, while about 75 hours would be required to reduce the oxygen to 16 per cent and increase the carbon dioxide to 5 per cent. "In this extreme case, the physical change is seen to be much more dangerous than the chemical."

B. CARBON DIOXIDE AS AN INDEX OF VENTILATION REQUIREMENTS

Measurement of carbon dioxide concentrations in spaces occupied by human beings had been standard among ventilating engineers for many years until Yaglou, Riley, and Coggins[2] reported in 1936 their results from a series of experiments on ventilation requirements. They concluded that the carbon dioxide concentration "in the air of occupied rooms proved to be an unreliable index of ventilation, from the standpoint of both outdoor air supply and odor intensity" and suggested that "a great deal of unjustified effort would be saved by discontinuing the usual measurements of CO_2 in ordinary ventilation work, except perhaps in instances in which the air flow is well under 10 c.f.m. per person."

Many research workers and writers during the present century have recognized that the existence of 0.10 to 0.50 per cent CO_2 in spaces occupied by human beings is not of itself dangerous. Some still express the belief, however, that such an increase in carbon dioxide, from a normal outdoor level of 0.03 to 0.04 per cent, indicates the presence of unhealthful constituents as a result of *vitiation of air* by human respiration. This question has not been settled to the satisfaction of the layman. The current use of odors as indexes of ventilation requirements is still suspected by some as neglect of a fundamental hazard to life and health. Nevertheless, public health workers and sanitary ventilation engineers are generally convinced at present that oxygen and carbon dioxide concentrations in air at normal barometric pressures are not of concern to health in the absence of more substantial disturbances of air composition, such as operation of industrial processes, or storage of foods that consume oxygen or generate carbon dioxide.

The extended use of odor-controlling processes for air conditioning will bring about further revisions in the standards of quantities of outdoor air per capita

[1] C. O. Mackey, *Air Conditioning Principles*. International Textbook, Scranton, 1941.

necessary for health or comfort. Eventually it may be possible to approve 100 per cent recirculation of indoor air on the strength of the unavoidable fact that some outdoor air will force its way through a conventional structure in spite of any attempt to create a self-contained space. Certainly the possibility of operating an air-conditioning system without the use of outdoor air will depend upon future discoveries in the realm of air "freshness" and whether it proves possible to convince most persons that a synthetic environment is just as "fresh" and healthful as outdoor air.

Ventilation rates for the control of tobacco smoke and body odors in various applications are suggested in Table 2.

TABLE 2

Recommended Quantities of Outdoor Air Per Person[a]

Outdoor air c.f.m./person	Type of space or occupancy
5–10	High-ceiling space such as: bank, auditorium, church, department store, theater; room with no smoking
10–15	Apartment, barber shop, beauty parlor, hotel room; room with light smoking
15–20	Cafeteria, drug store with lunch counter, general office, hospital room, public dining room, restaurant; room with moderate smoking
20–30	Broker's board room, private office, tavern; room with heavy smoking
30–40	Cocktail bar, director's conference room, night club; room with heavy smoking

[a]Air-cleaning or odor-adsorbing devices not used. (Space not less than 150 cu. ft. per person, or floor area not less than 15 sq. ft. per person.)

State and city codes should be consulted to make certain that minimum outdoor-air requirements are followed.

C. EFFECT OF ROOM SIZE ON PER CAPITA VENTILATION REQUIREMENTS

A series of experiments[2, 3] on ventilation requirements for human occupancy demonstrated that

> "air space per occupant in a room not only affects the disappearance rate of body odors and hence ventilation requirements, but also the efficiency of ventilation systems. Large rooms have an advantage over small ones, as they act like reservoirs, allowing body odors to disappear with a minimum supply of outdoor air and maximum ventilation efficiency. A small room would require a greater air supply per occupant for the control of body odor. An increased air supply entails a loss of ventilation efficiency, as the air passes quickly to the exhaust without removing a full share of odors, heat, and moisture."[3]

Table 3 summarizes the results of these experiments.

[2] C. P. Yaglou, E. C. Riley, and D. I. Coggins, *Trans. ASHVE*, **42**, 133 (1936).
[3] C. P. Yaglou and W. N. Witheridge, *Trans. ASHVE*, **43**, 423 (1937).

TABLE 3

Requirements of Outdoor or Odor-Free Air for Dilution of Body Odors[2]

Air space cu. ft./person	Clean air supply, c.f.m./person[a]	Type of occupants and kind of ventilating equipment[b]
A 100	29	School children; av. personal hygiene
100	25	Sedentary adults
100	22	School children; best personal hygiene
B 200	38	School children; poor personal hygiene
200	23	Laborers
200	21	School children; av. personal hygiene
200	18	School children; above av. personal hygiene
200	16	Sedentary adults
C 200	12	Sedentary adults; air washed by centrifugal atomizing humidifier
200	<4	Sedentary adults; summer season; air cooled and dehumidified by spray washer; water changed daily
D 300	17	School children
300	12	Sedentary adults
E 500	11	School children
500	7	Sedentary adults

[a]Based on impressions of persons entering experimental room from relatively clean air at "threshold" odor intensity. Allowable odor intensity of 2 on a scale ranging from 0 for no perceptible odor to 5 for nauseating or overpowering odor.

[b]Heating season, air not washed or conditioned, except as noted in Group C tests at 200 c.f.m. per person.

With respect to tobacco odors, however, their tendency to become more offensive during the first few hours after smoking indicated that retaining them longer in the occupied space by increasing the volume of the space actually was a handicap. The conclusion was that for control of tobacco smoke by dilution ventilation small volumes of air space and high ventilation rates per capita would be a preferable combination, in spite of the probably decreased efficiency of air-supply utilization.

D. MINES, TUNNELS, AND UNDERGROUND SPACES

Man has burrowed underground for many years, and the deeper he goes, the more acutely conscious he becomes of excessively high temperatures and humidities and the presence of dangerous gases. The removal of industrial and residential quarters to underground air-raid shelters, as practiced in Europe and Asia during World War II, promises to make the ventilating and air-conditioning engineer a more essential member of the industrial-design organization than he has ever been in the past. The conditioning of underground residential and industrial spaces is somewhat akin to the highly important air conditioning for submarine and stratosphere transportation, and is already an indispensable factor in the deep mines of South Africa.

The specialized problems of mine ventilation will not be discussed here. The reader is referred to comprehensive publications on this subject.[4–8a]

II. General Industrial Ventilation

General ventilation may be classified in many ways to accommodate such distinctions as (*1*) natural or mechanical, (*2*) supply or exhaust, (*3*) nondirectional or directional, and (*4*) anemotive or gravity. Each of these groupings is essentially an abbreviated definition of the possible features of general ventilation. A descriptive classification is suggested below:

A. CLASSIFICATION OF GENERAL INDUSTRIAL VENTILATION

1. Natural General Ventilation

Anemotive ventilation: air passing transversely through a space as a result of horizontal wind forces. The aeromotive forces also can be vertical as a result of suction produced on the roof of a building when subjected to substantial wind velocity.

Thermal or gravity ventilation: air movement produced by convection currents or indoor-outdoor temperature differences.

2. Mechanical General Ventilation

Nondirectional: (*1*) Supply, pressure, or plenum ventilation: air supplied to a space so as to create a *very slight* pressure, which forces air outward through any available opening, in the absence of wind pressure of greater magnitude. Distribution of the air supply must be fairly uniform to produce nondirectional general ventilation. (*2*) Exhaust, suction, or vacuum ventilation: air removed from a space so as to create a *very slight* reduction in pressure, which causes outdoor air to force its way in through any available opening.

Directional: (*1*) Localized dilution by air supply; also termed "forced dilution" and "forced diffusion": clean air is *blown* across the work area toward the source of contamination to diffuse a contaminant into the large air reservoir of the room. The principle objections to this method are the dangers of creating excessive drafts on workers and of blowing contaminants through the workers' breathing zone. (*2*) Localized dilution by air exhaust: clean air is *exhausted* across the work area toward the source of contamination, but no exhaust hood or process enclosure is provided. This method of ventilation is good evidence of the close relation between general and local ventilation; it is precisely the same as moving a process close to a wall-type exhaust fan to take advantage of the gradually increasing velocity as the air approaches the fan.

[4] G. E. McElroy, *U.S. Bur. Mines Bull.* No. **385** (1935).
[5] D. Harrington and S. J. Davenport, Part 1, *U.S. Bur. Mines Circ.* No. **7001** (1938); Part 2, *ibid.*, No. **7182** (1941).
[6] D. Harrington, *U.S. Bur. Mines Circ.* No. **7047** (1939).
[7] R. R. Sayers, *U.S. Bur. Mines Circ.* No. **7221** (1942).
[8] D. Harrington, *Heating, Piping, Air Conditioning*, **17**, 275 (May, 1945).
[8a] G. E. McElroy, A Mine Air-Conditioning Chart, *U. S. Bur. Mines Repts. Investigations* No. **4165** (1947).

B. GENERAL VENTILATION SPECIFICATIONS

There are in current use the following methods of specifying general or space ventilation rates: (*1*) air changes per hour (Table 4); (*2*) minutes per air change (Table 4); (*3*) air flow per square foot of floor (Table 5); (*4*) air volume on a per capita basis (Table 2); (*5*) air volume required to dilute known or predictable concentrations of air contaminants to safe or acceptable levels.

The following example illustrates the interrelationships between the first four methods of specifying space ventilation:

Assume a classroom with the following dimensions:

10 ft. ceiling
15 sq. ft. of floor area per person
150 cu. ft. of air space per person

The following ventilation rates are identical for this room:

30 c.f.m. per person
2 c.f.m. per square foot of floor area (30/15)
5 minutes per air change (150/30) or (10/2)
12 air changes per hour (60/5)
120 c.f.h. per square foot of floor (12×10) or (2×60)
1800 c.f.h. per person (12×150) or (120×15) or (30×60)

1. General Ventilation Rates in Terms of Air Changes

The amount of ventilation for a room or building is commonly expressed as the number of times per hour that a complete change of air is effected, or as the number

TABLE 4
Air-Change Rates for General Ventilation

Type of room or building, public and industrial	Air changes/hour		Minutes/air change	
	Low	High	Slow	Fast
Auditoriums; assembly halls	4	30	15	2
Bakeries	10	60	6	1
Boiler rooms; engine rooms	4	60	15	1
Corridors; hallways; lobbies	1	10	60	6
Dairies; creameries	5	30	12	2
Foundries, ferrous	4	30	15	2
Foundries, nonferrous	6	60	10	1
Garages, storage and parking	3	20	20	3
Garages, repair	6	30	10	2
Hospitals, ordinary	2	15	30	4
Kitchens, commercial	10	60	6	1
Laboratories, chemical	6	30	10	2
Laundries; pressing shops	10	120	6	½
Locker rooms	2	15	30	4
Machine shops	3	20	20	3
Offices, general and private	2	30	30	2
Restaurants; cafeterias	4	30	15	2
Residences (excluding kitchen)	1	6	60	10
Retail stores	6	20	10	3
Smoking rooms; lodge rooms	10	60	6	1
Toilets; bathrooms	10	30	6	2
Waiting rooms; lounges	3	10	20	6
Warehouses	1	6	60	10

of minutes required to produce one complete change of air. The mathematics of the air-change method of estimating ventilation assumes that air distribution is uniform throughout the room or building. In practice such ideal distribution is seldom, if ever, accomplished. Furthermore, the dilution of contaminants is a gradual process and, even after the contaminating operation is discontinued, it may take hours to clear the space by general ventilation.

The wide range of values in Table 4 makes it evident that a good deal of judgment is necessary in selecting the proper rates of air change. Experienced designers usually check ventilation estimates by at least two methods of computation, if alternate data are available. General ventilation requirements should not be estimated in terms of air changes if harmful, irritating, offensive, or flammable air contaminants are dispersed by activities within the occupied space. In such cases the required ventilation is the amount needed to dilute the estimated or measured air contamination down to a permissible concentration. However, control by dilution may not be the best solution; local exhaust ventilation is especially suitable when the types and concentrations of air contaminants from a single process can vary from time to time.

2. General Ventilation Rates Based on Floor Area

When the specific equipment or per capita requirements are not known, it is convenient to estimate ventilation on the basis of the amount of floor area devoted

TABLE 5

General or Space Ventilation Rates Based on Floor Area

Ventilation/sq. ft. of floor		Type of room, building, or process
c.f.m.	c.f.h.	
1	60	General industrial buildings having no localized sources of unhealthful, irritating, flammable, or explosive air contaminants
1	60	ASHVE recommended rate for storage garages mechanically ventilated (either supplied or exhausted air)
2	120	Workrooms containing "heated surfaces" covering 10% of the floor area[9]
1.5	90	Gymnasiums; dance halls
3	180	Bath and toilet rooms
2	120	Battery charging rooms
3	180	Small repair garages
1.5	90	Large dining rooms
2	120	Small dining rooms
2	120	Spacious kitchens
4	240	Average restaurant kitchens
10	600	Small congested kitchens
50	3000	Enclosures or booths for arc welding
100	6000	Rooms for abrasive blasting or metal spraying (supplied-air helmets required for workers)

[9] *Tentative Recommended Good Practice Code and Handbook on the Fundamentals of Design, Construction, Operation and Maintenance of Exhaust Systems.* Am. Foundrymen's Assoc., Chicago, 1938.

to known kinds of activity. Obviously a continuously changing factory layout interferes with the most economical use of ventilating air. However, one important advantage in this method of specifying ventilation is that air-flow rates are independent of ceiling heights. The air-change method, on the contrary, penalizes the designer who provides an extra-high ceiling because it requires greater quantities of air to comply with some predetermined air-change figure based only on the type of industry. Actually, high ceilings in industrial buildings reduce rather than increase the required mechanical-ventilation rate, so far as the ground-floor-level working zone is concerned.

Table 5 gives a few examples of values used with this method of estimating ventilation.

3. Dilution Ventilation (General and Local)

If enough clean air is mixed with contaminated air, the concentration of the contaminant may be diluted to any reasonable level. It is obviously an advantage to know both the initial and desired concentrations and the efficiency of diffusion if the requirements of this method are to be predicted successfully. For many years the application of dilution ventilation has been largely experimental, empirical, or trial-and-error on the basis of visual or sensory observations of the *before and after* levels of contamination.

A simple formula is available for computing the required amounts of clean air for dilution purposes when the quantities of air contaminant produced and the concentration that may be permitted in the human environment are known or are capable of estimate:

$$AC = \frac{\text{contaminant released (c.f.m.)}}{\text{dilution air required (c.f.m.)}}$$

where AC = allowable concentration of contaminant in volumetric units, and c.f.m. = cubic feet per minute.

The above formula requires that the *allowable concentration* be expressed in parts of contaminant per million parts of air, and indicates that the p.p.m. figures in common use by industrial hygienists can be used directly in dilution-ventilation specifications by translating "parts per million" into the expression "cubic feet of contaminating gas or vapor per million cubic feet of air." Therefore, if it is estimated that an internal combustion engine produces 60 c.f.h. of carbon monoxide or 1 c.f.m. CO, and the allowable concentration is 100 p.p.m. CO:

$$AC = 100 \text{ p.p.m.} = \frac{100}{1{,}000{,}000} = \frac{1(\text{c.f.m. CO})}{x(\text{c.f.m. air})}$$

where x = 10,000 c.f.m. air to maintain 100 p.p.m. CO.

If the allowable concentration is expressed in gravimetric units, the amount of contaminant produced should be estimated correspondingly on the weight basis so that a simple dilution formula can be used for computing general ventilation. For example, assume that an arc welding operation generates 1000 mg. of fume per minute and that a fume concentration of 10 mg. per cubic meter of air is permissible:

$$AC = \frac{10 \text{ mg.}}{\text{cu. m.}} = \frac{1000 \text{ (mg. fume per minute)}}{x \text{ (cu. m. of air per minute)}}$$

where $x =$ 100 cu. m. of air per minute, or 3500 c.f.m. to maintain a fume limit of 10 mg. per cubic meter (using a rounded figure of 35 cu. ft. per cubic meter).

It is important to observe that any mathematical expression, as outlined above, assumes 100 per cent uniformity and thoroughness of mixing of contaminant with air. Obviously a correction must be applied to such a theoretical result, and at this point the designer's experience and judgment must enter. In general, it is recommended that dilution efficiency be anticipated in the range of 25 to 50 per cent, which means that 2 to 4 times the theoretical air volumes should be provided in the capacity of the actual installation. If the worker is near the source of air contaminants, this method of computation should be used only for estimating the order of magnitude of local exhaust ventilation required. Used in this manner, it serves as a check on the ventilation rates determined from minimum controlling air velocities and maximum areas through which the contaminant may escape.

4. General Ventilation for Control of Solvent Vapors

General ventilation is occasionally the only practical method of controlling solvent vapors arising from industrial operations covering large areas of a plant. Ventilation requirements are based on the volumes of air needed to dilute the vapor concentration to a safe or satisfactory level.

TABLE 6

General Ventilation Requirements for the Control of Solvent Vapors[a]

Liquid		Requirements for Health		Requirements for Fire Prevention	
Chemical name	Vapor, cu. ft./pt. liquid at 70° F.	Allowable concentration for human exposure 8 hr./day (p.p.m.)[b]	Air, cu. ft./pt. liquid evaporated (nearest 1000)	Allowable concentration for fire safety 1/5 lower explosive limit (p.p.m.)[b]	Air, cu. ft./pt. liquid evaporated (nearest 100)
Acetone	5.5	500	11,000	5,100	1,100
Amyl acetate	2.7	200	14,000	2,200	1,200
Benzene	4.6	100	46,000	2,700	1,700
Butyl acetate	3.1	200	16,000	2,800	1,100
Carbon disulfide	6.7	20	335,000	2,500	2,700
Carbon tetrachloride	4.2	50	84,000		
Diethyl ether	3.9	500	8,000	3,700	1,100
Ethyl acetate	4.1	200	21,000	4,400	900
Ethylene dichloride	5.1	100	51,000	12,400	400
Gasoline	3.0[c]	500	6,000	2,800	1,100
Methyl alcohol	10.1	200	50,000	13,400	800
Toluene	3.8	200	19,000	2,500	1,500
Trichloroethylene	4.5	200	23,000		
Turpentine	2.6	200	13,000	1,600	1,600
Xylene	3.3	200	17,000	2,000	1,700

[a]Air volumes are based on quantities of solvent evaporating into the workroom. Quantities of air required per minute or per hour must be determined by estimating the solvent losses in pints per minute or per hour.

[b]p.p.m. = parts of vapor per million parts of air; 1 per cent equals 10,000 p.p.m.

[c]Approximate.

Table 6 indicates the large differences between the dilution air volumes required for fire prevention and for the prevention of illness or occupational disease. The required volumes of air stated in this table would apply only if completely uniform distribution of air supply were possible. Furthermore, it is assumed that vapors are *released* uniformly throughout the room. Inasmuch as neither of these conditions is probable, and since workers are usually rather near the evaporating solvent, it is therefore recommended that the designer provide at least twice the amounts of air given in Table 6.

5. Vapor Equivalents of Liquids or Solvents

The amount of pure vapor formed at sea level by the evaporation of a known volume or weight of liquid can be calculated by one of the following formulas:

$$\text{(A)} \quad \frac{\text{cubic feet of vapor}}{\text{pound of liquid}} = \frac{(\text{liters per mole})(\text{grams per pound})}{(\text{liters per cubic foot})(\text{grams per mole})}$$

$$\text{(B)} \quad \frac{\text{cubic feet}}{\text{pound}} \text{ at } 0^\circ \text{ C.} = \frac{(22.41)(453.6)}{(28.32)(\text{mol. wt.})} = \frac{359}{\text{mol. wt.}}$$

$$\text{(C)} \quad \frac{\text{cubic feet}}{\text{pound}} \text{ at } 70^\circ \text{ F.} = \frac{(530)(359)}{(492)(\text{mol. wt.})} = \frac{387}{\text{mol. wt.}}$$

$$\text{(D)} \quad \frac{\text{cubic feet}}{\text{pint}} \text{ at } 70^\circ \text{ F.} = \frac{(387)(1.041)(\text{sp. gr.})}{\text{mol. wt.}} = \frac{403 \text{ (sp. gr.)}}{\text{mol. wt.}}$$

$$\text{(E)} \quad \frac{\text{cubic feet}}{\text{pint}} \text{ at } 25^\circ \text{ C.} = \frac{(537)(403)(\text{sp. gr.})}{(530)(\text{mol. wt.})} = \frac{408 \text{ (sp. gr.)}}{\text{mol. wt.}}$$

1.041 in equation (D) is pounds of water per pint at 70° F.
22.41 in equation (B) is liters per mole at 0° C.
28.32 in equation (B) is liters per cubic foot
453.6 in equation (B) is grams per pound
492 in equation (C) is 0° C. in Fahrenheit degrees absolute
530 in equation (C) and (E) is 70° F. in degrees absolute
537 in equation (E) is 25° C. in Fahrenheit degrees absolute

For ventilation estimates, a constant of 400 in equation (C) above is quite satisfactory, and has been recommended by Hemeon.[10, 11] Equation (D) or (E) may be combined with the allowable concentration on page 284 to simplify the determination of ventilation required for adequate dilution. In the following equation, allowable concentration must be in parts of vapor per million parts of air:

$$\frac{\text{c.f.m. air}}{\text{pint of liquid}} = \frac{400{,}000{,}000 \text{ (specific gravity of liquid)}}{(\text{allowable concentration})(\text{molecular weight})}$$

Thus, if the designer is given an allowable concentration for trichloroethylene of 100 p.p.m., the dilution ventilation for 100 per cent efficient distribution would be:

$$\frac{\text{c.f.m.}}{\text{pint}} = \frac{(400{,}000{,}000)(1.5)}{(100)(131)} = 45{,}000 \text{ (approx.)}$$

[10] W. C. L. Hemeon, *Heating & Ventilating*, **37**, 39 (Nov., 1940); **37**, 42 (Dec., 1940); **38**, 40 (Feb., 1941); **38**, 71 (Mar., 1941).

[11] W. C. L. Hemeon, *Heating & Ventilating*, **42**, 95 (Dec., 1945).

C. DISPERSION OF AIR CONTAMINANTS BY GENERAL VENTILATION

One of the important disadvantages of general ventilation is that it permits the building or room to become a large settling chamber for any dusts, fumes, or mists suspended in the air, even though the concentration may be within acceptable limits so far as health and safety are concerned. This has been most dramatically demonstrated in plants manufacturing or using highly flammable metal dusts. Although the dust concentrations at any one time were not sufficient to constitute a nuisance or hazard, the accumulation over many months or years has resulted in disastrous explosions of dust that had been deposited on rafters and inaccessible machinery surfaces.

In some cases the settling or separation of contaminants from the air may represent condensation of materials, vaporized by high-temperature processes, which may accumulate on all surfaces with ever increasing danger. Serious flash fires have occurred where the interior surfaces of the building were well impregnated or saturated with condensed vapors of flammable liquids or waxes. Even in our homes, laboratory tests have shown "that some of the fish fried on the stove is likely to condense on an upstairs window pane in a matter of seconds."[12]

D. PROVISIONS FOR MAKE-UP AIR

The Industrial Hygiene Codes Committee[13] of the American Foundrymen's Association formulated the following requirements for replacement of air removed from a building by extensive exhaust ventilating equipment:

"Section X: Provisions for Make-Up Air

"(A) *General Requirements.* When the amount of air exhausted from a workroom or building exceeds six times the cubical contents per hour of such workroom or building, clean, fresh air shall be admitted into the workroom or building by intake vents or positive mechanical fans to make up the difference between the amount exhausted and at least six times the cubical contents.

"Means shall be provided for heating the make-up air to maintain the proper temperatures within the workroom or building. These provisions may be ignored in warm weather if windows and doors are kept open which will permit the make-up air entering such openings.

"(B) *Controlled Air Conditions.* Whenever exhaust systems are operating in workrooms or buildings wherein there is air conditioning or a high degree of air cleanliness is required, the amount of fresh make-up air to be supplied shall be at least ten per cent greater than that exhausted and means shall be provided for cleaning such make-up air consistent with the degree of air cleanliness required.

"(C) *Admission of Fresh Air.* Whenever it shall be necessary to provide a supply of make-up air to a workroom or building, either by means of intake vents or positive mechanical fans, to replace the air exhausted, the location of the points of intake shall be carefully considered.

"If intake vents are used, they shall be ample in size for the admission of the required amount of air.

"The admission of air to a work place or room shall be in the vicinity of the equipment or process being exhausted in order to keep to a minimum, disturbing drafts within the room.

"The draft caused by the discharge of air from any intake or pipe from a fan into a work

[12] G. Nelson and H. Wright, *Tomorrow's House.* Simon and Shuster, New York, 1945.

[13] *Tentative Recommended Good Practice Code and Handbook on the Fundamentals of Design, Construction, Operation and Maintenance of Exhaust Systems.* Am. Foundrymen's Assoc., Chicago, 1938.

place or room shall not exceed 100 feet per minute at any point within eight feet of the floor line, and the discharge air should be so directed that it does not blow directly on the operators or disturb any of the exhaust systems.

"(D) *Filtered Fresh Air.* If the general atmosphere outside the building is dusty and dirty and is not as clean as the air in the work room or building, all of the make-up air supplied shall be filtered to remove the impurities before admitting the make-up air inside."

1. Airbound Rooms and Buildings

General ventilation is nature's method. It is highly effective in the summertime with wide-open buildings, and in parts of the country where it seldom gets cold enough to worry about heat loss. To duplicate natural summertime ventilation we would need air-exchange rates through buildings of 60 to 600 air changes per hour instead of the conventional mechanical ventilation of 6 to 60 changes. In reality, the mechanical ventilation of large spaces with more than 15 air changes per hour becomes a tremendous air-handling problem.

When doors and windows are closed, prevailing winds no longer produce indoor air movements of several hundred feet per minute. Infiltration through the modern industrial structure may be as low as ¼ to ½ air change per hour (see Table 7). As winter approaches, and the building is barricaded against the weather for a substantial part of the year, the need for special air-supply openings to introduce make-up air is soon apparent.

No matter how simple, flexible, or universal general ventilation may seem at first glance, some plants discover that the great volume of air required, overloading of the heating plant, and special equipment needed to introduce enough tempered make-up air, all combine to make general ventilation a costly process in cold climates. The solution in many cases is to provide a compact local exhaust system that removes only a small quantity of air from the space, possibly so small that the normal infiltration of ½ to 3 air changes per hour will provide all the make-up air

TABLE 7

Air Infiltration Due to Natural Forces and Traffic[a]

Type of space	Air changes per hour
Room with no windows or outside doors	½ – ¾
Narrow room, windows in long wall, inside door	¾ – 1
Narrow room, windows in short wall, inside door	½ – ¾
Square room, windows in one wall, inside door	1 – 1½
Room with windows in two walls, inside door	1½ – 2
Room with windows in three walls, inside door	2 – 2½
Office building lobby, swinging doors	2 – 6
Store or restaurant, many door openings per hour	3 – 5
Department store, swinging doors with vestibule	½ – 3
Factory building, modern tight construction, large floor area in proportion to wall area	¼ – 1
Factory building, conventional construction	½ – 3
Factory building, large window areas, poor construction	2 – 6

[a]ASHVE 1948 *Guide* suggests that one half the window infiltration may be used in case of weatherstripping or storm sash.

required; or the handling of a small quantity of air close to the source of air contamination may permit the economical use of air-cleaning units so that air used for dust control can be returned to the workroom.

2. Estimating Infiltration by the "Crack Method"

The ASHVE *Guide*[14] makes the following suggestions for determining the actual length of window and door crack responsible at any one time for permitting air flow through a building:

(*a*) If a building has more than one room, divided by interior walls or partitions, it is sufficiently accurate to use half the total computed crack length in feet for all outside walls.

(*b*) For infiltration through a single room with one exposed wall, compute all the window and door crack length.

(*c*) In a room having two or three exposed walls, or a building with no partitions, use the amount of crack in the wall having the largest quantity, but in no case use less than half the total crack length in all walls.

Table 8 lists the experimentally determined infiltration rates through window and door cracks, and Table 9 gives the porosity of a few types of walls. The advantage of good plastering when walls are porous is very apparent.

TABLE 8

Air Infiltration Through Window and Door Cracks, Cubic Feet per Foot of Crack per Hour[a]

Type of opening	Condition	Wind velocity, miles per hour			
		5	10	20	30
Double-hung wood sash window (unlocked)	Average, nonweatherstripped	7	21	59	104
	Average, weatherstripped	4	13	36	63
	Poorly fitted, nonweatherstripped	27	69	154	249
	Poorly fitted, weatherstripped	6	19	51	92
Double-hung metal window	Locked, nonweatherstripped	20	45	96	154
	Unlocked, nonweatherstripped	20	47	104	170
	Unlocked, weatherstripped	6	19	46	76
Rolled section steel sash window	Industrial, horizontally pivoted	52	108	244	372
	Public building, projected	20	52	116	182
	Average residential casement	14	32	76	128
	Average heavy casement	8	24	54	92
Door	Well fitted, nonweatherstripped	27	69	154	249
	Well fitted, weatherstripped	14	35	77	125
	Poorly fitted, nonweatherstripped	54	138	308	500
	Poorly fitted, weatherstripped	27	69	154	249

[a]Adapted from ASHVE 1948 *Guide*.

3. Cost of Heating Make-Up Air

The total amount of "sensible" heat lost when 1000 cu. ft. of air is removed from an industrial building each minute for 1200 hours during the heating season

[14] American Society of Heating and Ventilating Engineers *Guide*, 1948 (published annually).

TABLE 9

Air Infiltration Through Walls, Cubic Feet per Square Foot of Wall per Hour[a]

Type of wall	Wind velocity, miles per hour			
	5	10	20	30
8½″ brick, unplastered	2.0	4.0	12	23
13″ brick, unplastered	1.0	4.0	12	21
Frame, with lath and plaster	0.03	0.07	0.18	0.26
8½″ brick, plastered	0.02	0.04	0.11	0.24
13″ brick, plastered	0.01	0.01	0.04	0.10

[a]Adapted from ASHVE 1948 *Guide*.
The brick walls listed in this table are walls that showed poor workmanship and were construeted of porous briek and lime mortar. For good workmanship, the leakage through hard brick walls with cement-lime mortar does not exeeed one third the values given.

from October through April is approximately 40,000,000 B.t.u. (British thermal units). This applies to Detroit or any other city having about the same length and severity of heating season (6000 to 6500 degree-days, see page 290).

This heat loss of 40,000,000 B.t.u. represents about 3 tons of coal at 55 per cent combustion efficiency; and at $10 a ton, the cost would be about $30 per season for an air-flow rate of 1000 c.f.m. Thus, a ventilating system that removed 100,000 c.f.m. from a building for 1200 hours during the industrial heating season would also remove $3000 worth of heat. This does not include the fixed costs such as depreciation, interest, and equipment maintenance, for which the ventilating system must be charged if the heating of make-up air requires an extended or new heating plant.

A new ventilating system should be charged for only the *additional* heat loss it creates. If its operation does not require a higher rate of fresh air supply than already exists because of infiltration, natural ventilating devices, or air-supply fans, then the new ventilating system will not increase the load on the heating system. On the other hand, the make-up air for a large exhaust system in a small shop may represent the greatest single item in the heating bill, and also might dictate the construction of a larger heating plant.

It is well to remember that some shops contain excessive heat even in the wintertime, and a new exhaust system installed to control smoke and fumes may relieve rather than aggravate inside temperature conditions. Skillfully located and distributed make-up air inlets in such cases may avoid the need for tempering the air to prevent cold drafts on workers. In view of the ever increasing interest in the possibility of recirculating indoor air for the purpose of saving heat energy, as well as the replacement of general ventilating systems with local exhaust systems handling much smaller volumes of air, two methods of predicting the magnitude of the heat quantities involved are given below. The second method employs the concept of the "degree-day," which is especially suitable for those who wish to estimate the heating costs imposed by their equipment in different parts of the country.

4. Heat Loss Analysis

(*a*) Assume 1000 c.f.m. make-up air.
(*b*) 0.0185 B.t.u. is required to raise 1 cu. ft. of air 1° F.
(*c*) Thus, 18.5 B.t.u. are required per °F. rise for 1000 c.f.m. of cold air supplied ($a \times b$).
(*d*) Also, 1110 B.t.u. are required per °F. for 60 minutes of operation at 1000 c.f.m. (60*c*).
(*e*) Also, 8880 B.t.u. are required per °F. for 8 hours of operation at 1000 c.f.m. (8*d*).
(*f*) Assume 150 days during industrial heating season (30 weeks at 5 days).
(*g*) Thus, 1,330,000 B.t.u. are required per °F. for 150 days operation at 1000 c.f.m. ($e \times f$).
(*h*) Assume 65° F. average temperature of air exhausted.
(*i*) Assume 35° F. average temperature of make-up air.
(*j*) Thus, 30° F. is average temperature differential ($h - i$).
(*k*) 40,000,000 B.t.u. are required for 1000 c.f.m. of make-up air per season ($g \times j$).

TABLE 10

Total Degree-Days for the Heating Season[15]

State	City	65° base	55° base
California	Los Angeles	1504	17
	San Francisco	3264	384
Colorado	Denver	5874	3440
Connecticut	New Haven	5895	3237
Illinois	Chicago	6290	3743
	Springfield	5373	3289
Indiana	Indianapolis	5298	2829
Iowa	Dubuque	6790	4468
Kentucky	Louisville	4180	2294
Maine	Eastport	8520	5236
	Portland	7012	4572
Maryland	Baltimore	4533	2491
Massachusetts	Boston	6045	3603
Michigan	Detroit	6490	4089
	Marquette	8693	5842
Minnesota	Duluth	9480	6774
	Minneapolis	7850	5417
Missouri	St. Louis	4585	2745
Nebraska	Lincoln	5999	3850
New Hampshire	Concord	7353	4640
New Jersey	Atlantic City	5176	2904
New Mexico	Santa Fe	6063	3106
New York	Buffalo	6822	4316
	New York	5347	3089
North Dakota	Bismarck	9192	6468
Ohio	Cincinnati	4703	3003
	Cleveland	6155	3795
Oregon	Portland	4469	1911
Pennsylvania	Philadelphia	4855	2695
	Pittsburgh	5235	3028
Utah	Salt Lake City	5555	3202
Vermont	Burlington	7514	4984
Virginia	Richmond	3727	1895
Washington	Seattle	4966	2185
	Spokane	6355	3672
Wisconsin	Green Bay	7825	5331
	Milwaukee	7245	4617

5. The Degree-Day

A useful device for estimating fuel consumption is the "degree-day" (item *m* in example below), which has been in use by heating and ventilating engineers since about 1925. By definition, "one degree-day is the product of one day and one degree difference in temperature between the maintained temperature and the outside air temperature during the day."[15]

The number of degree-days for any one day is the difference between the base temperature (usually 65° F.) and the mean outside temperature for the 24-hour period, if this mean is less than the base temperature. The expectable total degree-days for the heating season for a given locality is based on weather bureau records averaged for many years.

Table 10 gives the total seasonal degree-days for a number of cities in the United States. The 65° F. base is the one preferred for most heating-load estimates. It is assumed then that the indoor temperature will be near 70° F. The 55° F. base is used when the indoor temperature is maintained at a lower temperature, approximately 60° F.

6. Heat Loss Analysis Using Degree-Day Data

(*l*) Assume 210-day heating season (30 weeks at 7 days—see item *f* above).

(*m*) Also assume 6300 degree-days for 24-hour days ($j \times l$). (This figure is comparable to those in the degree-day table (Table 10), using the 65° F. base.)

(*n*) Thus, 2100 degree-days are represented by 8-hour days ($m/3$).

(*o*) And, 1500 degree-days are represented by 5-day weeks ($\frac{5}{7} \times n$).

(*p*) 26,640 B.t.u. are required per degree-day for 1000 c.f.m. ($3 \times e$).

(*q*) 40,000,000 B.t.u. are required for 1000 c.f.m. of make-up air per season ($o \times p$).

7. Heating Values of Various Fuels

The heating values of most fuels have been determined and reported in the technical literature.[15, 16] For estimating purposes in connection with the heat-loss analyses outlined above, the approximate values in Table 11 may be used.

TABLE 11

Heating Values and Fuel Efficiencies

Fuel	Approximate heat content, B.t.u.	Expectable efficiency, %	Available heat, B.t.u.
Coal	12,000/lb.	55	6,600/lb.
Oil	140,000/gal.	65	9,100/gal.
Natural gas	1,000/cu. ft.	75	750/cu. ft.
Manufactured gas	500/cu. ft.	75	375/cu. ft.

[15] C. Strock and C. H. B. Hotchkiss, *Degree Day Handbook*. Industrial Press, New York, 1937.

[16] ASHVE *Guide*, 1948.

E. AIR-SUPPLY INLETS AND EXHAUST OUTLETS

The design of ventilating equipment for an industrial plant is not complete without full consideration of the routes by which air will enter and leave the working areas. In fact, the ventilation route is important not only to the occupants of the building, but also to the neighbors and community at large. Industrial plants will not continue much longer to be huge settling chambers for particulate matter, and the demand for better inside conditions is gradually transferring the dust load from the inside to the outside, in the absence of air-cleaning equipment. Although the outdoor air has a tremendous ultimate capacity for absorbing air contaminants, the dilution process is by no means immediate, as those who are near some industrial plants will verify with enthusiasm.

The location of air inlets and outlets has the following significant aspects:

1. Air Inlets[17]

(*a*) Sufficient combined or total inlet area should be planned to accommodate the required volume of make-up air during the heating or cooling season, whichever needs the larger volume. This will prevent excessive inlet velocities that consume power, create drafts on workers, stir up dust, and interfere with local exhaust hoods. The chosen inlet velocity is likely to be an engineering compromise between low rates, which require large inlet areas, and high rates, which facilitate rapid dilution of contaminants.

(*b*) If widespread hazardous operations are controlled by dilution or general ventilation, inlets should be well distributed around the building to provide uniform circulation.

(*c*) If contaminants are controlled by *localized dilution*, or by forcefully diffusing them into the general room-air reservoir, inlets may be purposely located to give nonuniform air-supply distribution.

(*d*) Inlets should be located to take full advantage of any thermal or convection effects within the building. For this purpose the designer must avoid the location of inlets (and outlets) near the "neutral zone"[18] of inside-outside pressure differentials, which is approximately midway between the floor and roof.

(*e*) Inlets should be located remote from stacks or ventilators discharging contaminants from the same or neighboring structures.

2. Air Outlets

(*a*) Outlets should be located as far as possible from air inlets to prevent "short-circuiting." This advice should be followed for both natural and mechanical ventilation.

[17] The distinction between inlets and outlets is based on point of view; in this discussion, the point of reference is the occupied space, and not the interior of air ducts.

[18] J. E. Emswiler, *Trans. ASHVE*, 32, 59 (1926).

(*b*) As in the case of air inlets, if widely scattered operations are controlled by general dilution, outlets should be uniformly distributed around the building (see 1*b* above).

(*c*) As in the case of air inlets, if contaminants are controlled by localized dilution, air outlets may be purposely located to short-circuit a corner of a large room in order to create a high rate of air change there without involving the atmosphere of the entire space. This method of localized space ventilation requires a higher rate of exhaust air than supply air for the control area to prevent the spread of contaminants throughout the room (see 1*c*).

(*d*) Outlets should be placed to take full advantage of thermal effects (see 1*d*).

(*e*) Outlets should be protected against the direct force of prevailing winds, which reduce the capacity of exhaust fans when provided, or which destroy the anticipated air-flow route planned on the basis of thermal effects inside the building.

F. SHORT-CIRCUITING THE AIR FLOW

"Short-circuiting" usually implies that outdoor air is allowed to enter and leave a room by such a short route that it contributes very little to the air circulation and the dilution of impurities. This may occur with either natural or mechanical ventilation.

Short-circuiting is not, however, an invariable handicap. While short-circuited air escapes without conveying its share of general contamination, it likewise helps to conserve heat in the wintertime since it removes less heat than well-diffused air. If outdoor air can be short-circuited directly to an exhausted process without coming in direct contact with workers, substantial heat saving may be realized.

One designer, on observing that a large exhaust system was creating an air-bound room, decided to short-circuit the outdoor air directly to a large number of ventilated tanks, instead of passing it through the entire space between the building walls and the processing area. The cold air was brought in through vertical stacks located a few inches above each tank and it traveled horizontally to slot-type exhaust hoods. The low temperature of the air actually proved to be an advantage in holding it down near the tank surface, and since it did not pass through the working zone, no one was subjected to cold drafts.

G. SUCCESSIVE VENTILATION

A useful concept in the interest of air-handling economy is "successive ventilation." The air removed from an industrial plant frequently may be directed in a way that will provide both local and general ventilation. In fact, the air may be routed through several areas in succession, always in the direction of increasing air contamination, so long as the exhaust from one area is acceptable as the supply for the next area. The objective and result of successive ventilation is the saving of air-borne heat and air horsepower.

The following examples of successive ventilation will serve to suggest other applications:

Air from such areas as:	May be used to ventilate:
Corridors or hallways	Offices
Offices	Manufacturing areas
Manufacturing areas	Washrooms, toilet rooms
General manufacturing	Local exhausted processes
Theater auditoriums	Projection rooms
Kitchens	Hoods over ranges
Gymnasiums	Bathrooms, lavatories
Schoolrooms, classrooms	Cloakrooms, locker rooms
Dining rooms	Kitchens
Locker rooms	Toilet rooms

II. GENERAL VENTILATION VS. LOCAL EXHAUST VENTILATION

The art of industrial process ventilation has been somewhat evolutionary from the natural general ventilation achieved by correct design of industrial buildings for hot, humid, and dusty operations, to the highly effective local exhaust hoods in current use. Local ventilation prevents the spread of air contaminants throughout the building atmosphere with surprisingly small quantities of air flow in comparison with the volumes of air required by general ventilating systems. In spite of this characteristic air conservation of local ventilation, there are highly persuasive reasons why general ventilation still is selected by many industrial managements: (*1*) simplicity and economy of natural general ventilation; (*2*) relatively low first cost of mechanical general ventilation; (*3*) absence of interference with manufacturing operations; (*4*) flexibility in plants with constantly changing layouts; (*5*) existence of contaminating processes throughout the entire plant; (*6*) desire for large volumes of air circulation in hot weather; (*7*) discovery that local exhaust systems do not eliminate the necessity of supplying large volumes of heated air in the wintertime to replace that escaping from loosely constructed buildings by exfiltration. This volume of air change may be more than ample to control process air contaminants by the method of dilution, if means are provided to disperse contaminants from the immediate vicinity of the workers.

III. Industrial Process Ventilation

There can be no well-drawn line between general and local ventilation as applied to industrial processes, because even with only local exhaust provided, the result is some degree of general ventilation in the boundary zone between the room and the process. Local and general ventilation are somewhat analogous to local and general illumination, which we are just now learning to integrate for the highest visual efficiency.

In many plants the quantity of air handled by a local exhaust system is entirely adequate to provide simultaneous general ventilation for other parts of the plant. Air-intake openings can be placed so that air reaching the local exhaust hood passes over the largest possible surrounding area, thereby doing its full share of *general* ventilation. On the other hand, if a "short circuit" is allowed to exist between the exhaust hood and a near-by window or roof ventilator, some parts of the work space may receive no air circulation whatever.

A. INDUSTRIAL PROCESS ENCLOSURES

One serious disadvantage of general ventilation is the impossibility of recovering all the contaminant once it has escaped into the room atmosphere. Control is chiefly a matter of diluting the transient dusts or gases to a permissible concentration. The logical solution is to find some way to confine the contaminated air. In the event that a compact local exhaust hood around or close to the process is not feasible, the most suitable compromise is to enclose the entire process in a specially designed room.

The enclosure of a process to enable more satisfactory control of its atmospheric environment differs from general ventilation in the following two features:

(*1*) The concentration of contaminant within the room or booth may be several times the allowable exposure, and workers inside would then be required to wear respiratory protective devices to supplement the ventilation.

(*2*) The room or booth may be designed so that workers can perform their tasks from the outside or at the face of an opening. In this case the dust, mist, or fume concentration inside the booth is of no concern to the health of workers. Fire hazard or process visibility may then determine the standard of adequate ventilation.

1. Paint-Spraying Rooms or Booths

Paint-spray rooms that are open on one side are known as spray *booths*. Booths large enough for men to work inside, with or without respiratory protection, may be classed as a form of general ventilation, while those designed so that operators work outside might be rated as local exhaust hoods. Booths are a transition state between general and local ventilation; some classifications give them separate status, for convenience.

Clean air is drawn into the spray booth and across the worker's breathing zone. The usual method of specifying ventilation for spray booths is to state the velocity of air movement into the open face or side. Fifty linear feet per minute is very low velocity, suitable only for very large room-size booths, while 400 l.f.m. would be considered unnecessarily high for most jobs. The most widely accepted figure for small booths is 200 l.f.m. "face velocity" or 200 c.f.m. of air per square foot of face opening. Large booths operate satisfactorily on 100 l.f.m. for paints of low hazard, probably because the large mass of air moving toward the booth opening will control by the dilution process any escaping contamination.

2. Welding Booths or Rooms

Booths or rooms for welding vary from small square canvas enclosures, with rapid air change, to large permanent rooms. Quite often the booth will contain a local exhaust hood or downdraft ventilated bench. Ventilation requirements have been estimated in many ways, including: (*a*) c.f.m. based on size and kind of welding rods used; (*b*) c.f.m. based on weight of rod burned per minute; (*c*) c.f.m. based on power consumption at the arc; (*d*) optimum air velocity through a grille-top bench; (*e*) minimum air velocity into a "spot exhaust" hood at a specified distance from the

arc; and (*f*) desirable air movement past the worker's head. The use of so many estimating procedures shows that requirements can not be standardized. The best approach is to figure the ventilation rates by several methods to establish a reasonable agreement in the selection of air-flow constants.

A convenient rule of thumb for checking the amount of ventilation provided in welding booths or rooms is based on the rate of electrode burning. For coated steel rods, the ventilation rate to keep the fume concentration down to 10 or 15 mg. per cubic meter of air may be estimated by the formula:

$$\text{c.f.m.} = \frac{100{,}000\ (\text{in. diam. of electrode})^2}{\text{minutes per electrode}}$$

If welding is continuous by several persons simultaneously, the *minutes per electrode* in this formula include the idle time both during welding and during the exchange of electrodes. If welding is intermittent by one person, the *minutes per electrode* should be only the elapsed time to burn one full electrode; the ventilating fan may be turned off if welding is idle for extended periods. (See also section on dilution ventilation.)

3. Abrasive-Blasting Rooms

These are complete enclosures for sand blasting, shot blasting, grit blasting, hydroblasting, etc. The concentrations of dust in these rooms are enormous, and special supplied-air helmets must be provided for the workers. Preferably, complete protective suits are used because of the destructive effect of flying abrasive. Ventilation requirements are estimated either in (*a*) air changes per minute, (*b*) c.f.m. per square foot of floor area, or (*c*) c.f.m. per blasting nozzle in operation. Method (*c*) is used when the ventilation rates of similar blasting operations conducted in rooms of greatly different volumes are being compared. It is also a more rational method of relating ventilation to the amount of dust produced when the number of blasting operators in a given room varies. The ranges of ventilation rates used with these three methods of specification are: (*a*) 5–15 air changes per *minute;* (*b*) 50–150 c.f.m. per square foot of floor; and (*c*) 5,000–15,000 c.f.m. per nozzle in use.

4. Metalizing or Metal-Spraying Rooms

These may be similar to abrasive-blasting rooms, and the required personal protective equipment likewise similar, but without the necessity of protection against high-velocity abrasive particles. Spraying of metallic lead within a room results in a tremendous potential hazard, and the best possible supplied-air respirator is necessary even though the ventilation may be excellent.[19] Spraying of steel also creates a high concentration of particulate matter, but it is possible to design ventilating equipment that can prevent dangerously high air-borne concentrations; even so, the nuisance may not be tolerable, and some form of filter respirator might be required.

[19] H. I. Miller, Jr., G. M. Hama, E. C. J. Urban, and P. Drinker, *J. Ind. Hyg. Toxicol.*, **20**, 380 (May, 1938).

5. *Grinding Booths*

Booths for portable grinding processes have proved their practicability, and for many reasons of convenience and maintenance, seem to be superior to local exhaust hoods for snag-grinding wheels. Face velocities into grinding booths should prevent the escape of dusty air, but need not hold the large particles in suspension. Velocities of 100 to 300 l.f.m. are good practice.[20] Figures 1 and 2 illustrate two methods of designing booths, where the operator may be either inside or at the face of the process enclosure.

Figure 3 is a process enclosure closely related to the canopy-type hood, modified only by dropping the edges down around the operation to confine the air contaminant and reduce the required ventilation rate.

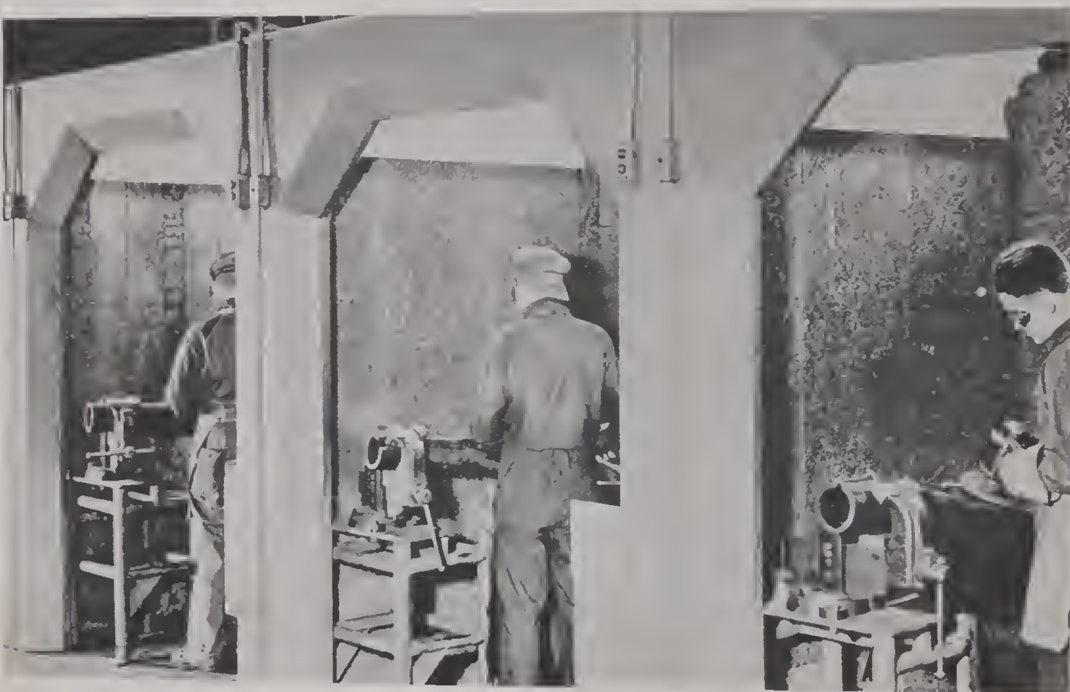


FIG. 1. Booth type enclosure for portable grinding—worker inside (*courtesy American Air Filter Co.*).

B. LOCAL EXHAUST VENTILATION

The air volume requirements for the control of air contaminants by general ventilation are many times greater than the volumes required with carefully designed local exhaust hoods. For this reason a word of caution is advisable before the characteristics of exhaust hoods are reviewed in detail.

Exhaust hoods occasionally cannot be used as originally intended by the designer; whereupon the factory operating personnel is inclined to modify the strategy

[20] J. M. Kane, *Foundry*, **74**, 90 (Aug., 1944).

FIG. 2. Booth for grinding magnesium castings combined with wet dust collector (*courtesy Peters-Dalton, Inc., Detroit*).

FIG. 3. Exhausted enclosure for car-wheel casting shakeout (*courtesy Claude B. Schneible Co.*).

of ventilation. In consequence, if an exhaust hood becomes nothing more than a device for creating general ventilation in the vicinity of a process conducted most of the time *beyond the effective range of the hood*, the designer's original estimate of required air-flow rates cannot apply. Furthermore, it would not be economical to increase the air-flow rate through such a local exhaust hood to bring it up to general ventilation volumes because the suction power requirements would be exorbitant. General ventilation should be provided by low-velocity, low-suction equipment. The warning, then, is *not to overestimate the capability of an exhaust hood as a general ventilating device.* Special systems of multiple hoods operating simultaneously in small rooms have been observed in some cases to give high rates of air change for the space. This condition is not a property of exhaust hoods, but instead the result of greatly reduced air space per hood.

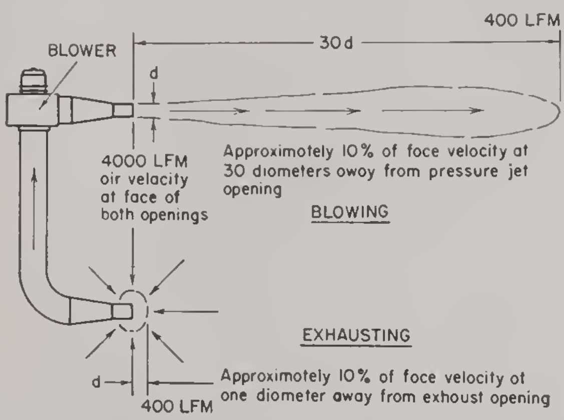


FIG. 4. Air-flow characteristics of exhausting and blowing devices.

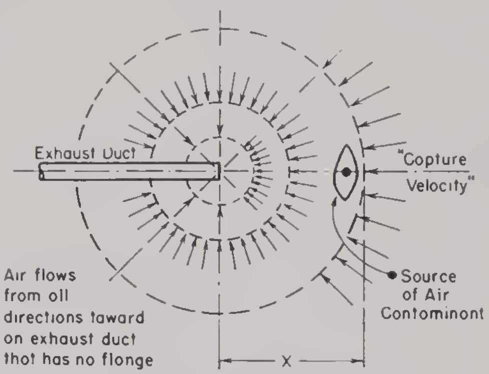


FIG. 5. Spherical nature of air flow into an unflanged and unobstructed exhaust hood.

1. Exhausting vs. Blowing

Figure 4 illustrates the fundamental difference between blowing and exhausting devices. Air blown from a small opening retains its directional effect for a considerable distance beyond the plane of the opening. However, if the flow of air through the same opening (or its equivalent in size) is reversed so that it now handles the same volume of air by exhaust, the flow becomes almost completely nondirectional and its range of influence is greatly reduced. It is for this reason that local exhaust hoods must not be contemplated for any process which cannot be conducted in the immediate vicinity of the hood.

2. DallaValle's Equation for Unobstructed Hoods

This equation is used to determine the relation between the quantity of air flowing into an exhaust hood and the resulting air velocity at a distant point along the hood centerline. The equation applies only when there is no obstruction between the hood opening and the control point in question (see Fig. 5).

A simplified form of the equation for both round and rectangular hood openings is as follows:

$$Q = V\left(\frac{X^2}{b} + A\right)$$

where A = area of hood opening in square feet, b = a constant that depends upon the shape of the hood, Q = quantity of air flow in c.f.m., V = centerline air velocity in l.f.m. at X feet from opening, and X = distance in feet from hood opening to control point.

DallaValle's equation is used frequently with a value of 0.1 for constant b, giving a simple approximate formula suitable for round or essentially square hoods. With this constant the equation is given in the convenient form: $Q = V(10X^2 + A)$. Table 12 lists the constants and equations for hood openings of various proportions.

3. *Flanges and Baffles Increase the Range of Exhaust Hoods*

Figure 6 illustrates the beneficial effect of restricting the direction of air flow into an exhaust opening. The diagrams were constructed on the basis of a point

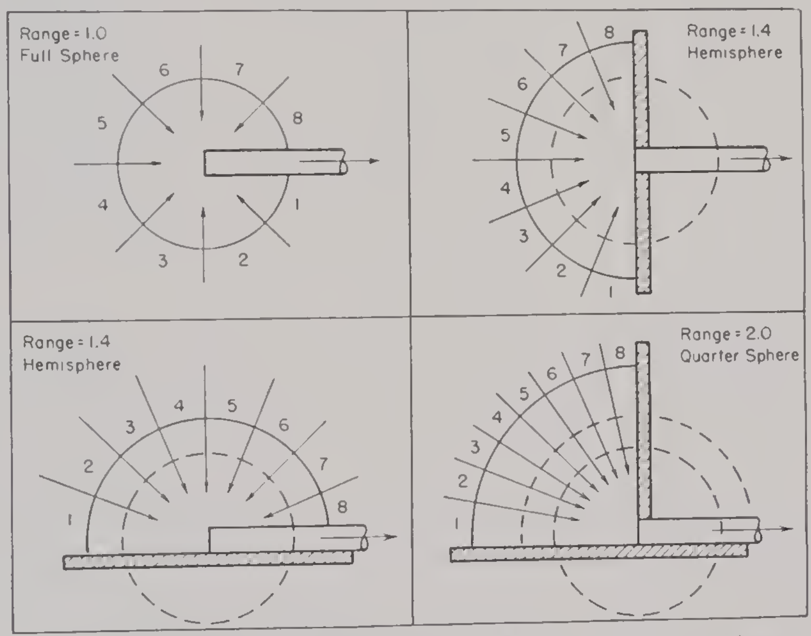


FIG. 6. Flanges and baffles increase the range of exhaust openings.

source of exhaust which, of course, does not occur in practice. Figure 7 shows the true velocity contours and streamlines for a rectangular hood, and indicates the marked deviation from spherical contours at points close to the hood face.[21] Figure 8 illustrates a flanged "spot exhaust" hood for arc welding.

Even though the true velocity contours of actual exhaust hoods are not strictly spherical or cylindrical, the error introduced by computing ventilating requirements on the basis of simple spheres, cylinders, or planes according to the hood design is

[21] J. M. DallaValle, *Exhaust Hoods.* Industrial Press, New York, 1941.

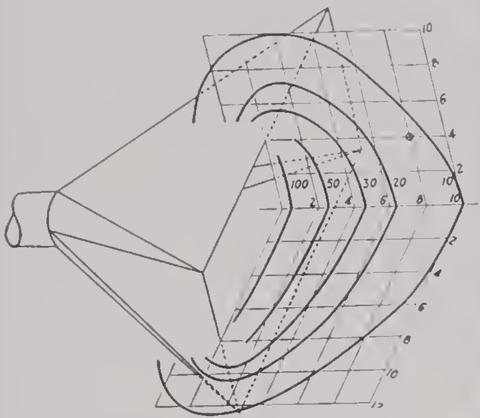


FIG. 7. Actual velocity contours and streamlines for air flow into a rectangular hood (*courtesy J. M. DallaValle*).

FIG. 8. Flanged exhaust hood for arc welding (*courtesy Ruemelin Manufacturing Co.*).

usually far less than the error entailed in estimating a successful *capture* or *dust control* velocity. Such estimates of required capture velocities may easily be 200 or 300 per cent in error if the field conditions are not carefully analyzed. Laboratory studies of capture velocities thus far have not been able to incorporate the highly complex disturbances encountered in most field applications. The ventilation designer must fill in this gap with all the experience and judgment he can command.

TABLE 12

DallaValle's Equation for Various Forms of Exhaust Hoods[21]

Shape of hood opening	Constant b	Equation
Circular	0.083	$Q = V(12X^2 + A)$
Square	0.083	$Q = V(12X^2 + A)$
Rectangular, sides in following proportions:		
10 × 9	0.081	$Q = V(12X^2 + A)$
10 × 8	0.078	$Q = V(13X^2 + A)$
10 × 7	0.075	$Q = V(13X^2 + A)$
10 × 6	0.071	$Q = V(14X^2 + A)$
10 × 5	0.065	$Q = V(15X^2 + A)$
10 × 4	0.059	$Q = V(17X^2 + A)$
10 × 3	0.049	$Q = V(20X^2 + A)$
10 × 2	0.037	$Q = V(27X^2 + A)$
10 × 1	0.020	$Q = V(50X^2 + A)$

4. Air Velocities for Control of Air Contaminants

The escape of air contaminants can be prevented by the use of sufficient "capture velocity" at the point where the manufacturing process generates or releases the contaminant. The required velocity is estimated with consideration of

drafts, traffic disturbances, convection currents, and mechanical motions around the ventilated process. Such estimates are very often necessarily speculative or trial-and-error values combining the designer's experience and judgment, and his appraisal of scattered reports of laboratory and field studies. Current research on this problem is certain to reveal, for future design, more rational ways to determine capture velocities for many types of processes.

Table 13 recommends tentative air velocities for the local-exhaust control of gases, vapors and fumes, and dusts below 10 μ in size. The density of gaseous contaminants is ignored on the assumption that the concentration in the air will be less than 1 per cent or 10,000 p.p.m. All figures are air velocities in l.f.m.; they are not hood-face velocities unless the process under control is at or within the hood opening. These velocities are recommended for applications where no baffles or windbreakers can be installed for deflection of cross drafts.

TABLE 13

Recommended Velocities to Prevent the Escape of Air Contaminants

Horizontal draft condition	Process at room temperature	Process several hundred degrees F. above room temperature, creating strong thermal updrafts		
	All hood types	Updraft hood	Sidedraft hood	Downdraft hood[a]
Negligible (50 l.f.m.)	75	100	200	300
Slight (100 l.f.m.)	150	200	300	400
Moderate (200 l.f.m.)	300	300	400	500
Strong (300 l.f.m.)	400	400	400	500

[a]Generally an unsatisfactory choice for hot processes.

Table 13 does not incorporate the important factor of the speed or force of dust or mist generation by certain kinds of industrial process. Spray-painting guns discharge a mist that has sufficient velocity to rebound with considerable force from large flat surfaces perpendicular to the line of aim. Stone cutting, crushing, and milling give a high initial velocity to particulate matter. Grinding, polishing, and buffing wheels remove particles at high speed, and also induce high-velocity air currents at their peripheries. Pneumatic tools scatter large and fine particles in all directions, and the designer must decide how large a piece he will attempt to capture with his exhaust hood. Capture velocities for this class of machine and hand tools range from 500 to 5000 l.f.m. depending on the degree of control desired.[22–25]

[22] "Fundamentals Relating to the Design and Operation of Exhaust Systems," *ASA-Z9* Am. Standards Assoc., New York, 1936.

[23] *Air Hyg. Foundation Am., Preventive Eng. Ser. Bull.* No. **2**, Part 4 (1938).

[24] F. F. Kravath, *Heating & Ventilating*, **39**, 35 (Apr., 1942).

[25] T. Hatch, *Mech. Eng.*, **58**, 109 (Feb., 1936).

5. *Specific Gravity of Gases and Vapors*

It is frequently stated that gases or vapors heavier than air should be ventilated downward, and those lighter than air should be removed from the room by updraft methods. Experience and research[26] indicate that it is quite important to consider the distribution, concentration, and temperature of the gas or vapor in the air before drawing any conclusion about the relative merits of updraft and downdraft systems of ventilation. This is especially true of general ventilation, where the forces influencing the rate of gas or vapor diffusion are complex and uncertain.

The following example illustrates the significance of vapor concentration:

Assume: that air contains 1 per cent or 10,000 p.p.m. of a vapor with a specific gravity of 5.0; assume also that the vapor is well mixed with the air in the ventilated area as a result of drafts, plant activity, and convection currents.

Then: air constitutes 99 parts having a sp. gr. of 1.0, vapor constitutes 1 part having a sp. gr. of 5.0,

$$\begin{aligned} 0.99 \times 1.0 &= 0.99 \\ 0.01 \times 5.0 &= \underline{0.05} \\ &\ 1.04 = \text{“effective” sp. gr. of the air–vapor mixture.} \end{aligned}$$

Therefore, the above mixture, compared with incoming clean air, would have a tendency to move downward expressed by the ratio 104/100, and not by the ratio 5/1, as is frequently implied. This means that, in industry, the effects of drafts, window ventilation, traffic disturbances, or process heat can easily dwarf into insignificance the effect of specific gravity.

Cleaning or degreasing liquids used on tables or at fairly stationary locations can be exhausted from the area by sufficient downdraft grille ventilation, whether the vapors are heavier or lighter than air. Updraft or backdraft hood ventilation is also practical if the correct amount of air is removed according to the distance of the hood from the point of operation. The important objection to updraft ventilation is *not* that it does not lift vapors that are heavier than air (which it does very well, in fact, at proper air-flow rates), but that it may draw these vapors across the worker's breathing zone. However, when a sufficient volume of upward air movement is utilized, even the objection to drawing the contaminant across the breathing zone may be "splitting hairs" in cases where other forms of ventilation are exceptionally difficult to apply.

6. *Canopy Hood Ventilation*

Figure 9 is a diagram of the familiar canopy or overhead hood. Simplified equations are suggested for estimating the correct amounts of ventilation for such hoods. Although the diagonal dot-dash line in the diagram should be considered the true "outer face" of the hood for the purpose of ventilation estimates, the four simple equations given make sufficient allowance for the resulting *geometric* error of

[26] W. N. Witheridge and H. T. Walworth, *J. Ind. Hyg. Toxicol.*, **22**, 175 (May, 1940).

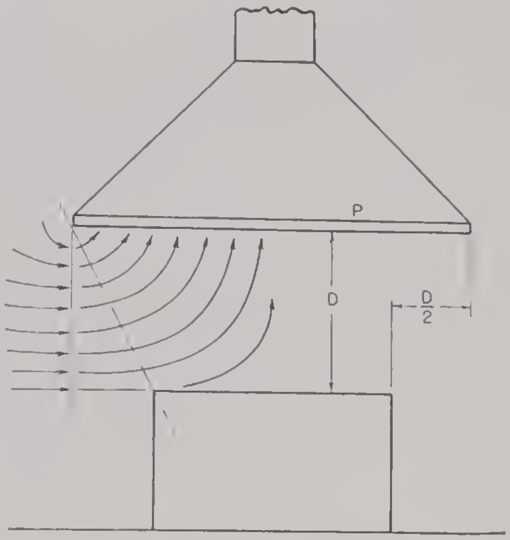


FIG. 9. Updraft or canopy-hood ventilation: c.f.m. = 75 DP (when drafts are negligible); c.f.m. = 100 DP (designers popular choice); c.f.m. = 150 DP (in presence of moderate drafts); c.f.m. = 300 DP (near strong, steady drafts); where c.f.m. = required air flow in cubic feet per minute; D = height of hood edge in feet above the point of air contamination; P = perimeter of hood at lower edge in feet, including only those sides open to the room; D/2 = extension of hood in feet beyond the source of air contamination on all sides open to the room. Constants in these equations are based on a hood extension of D/2. If the actual extension is less, compute the c.f.m. by assuming a D/2 extension, and use this resulting quantity of air flow divided by the hood area to determine the "face velocity" of the hood, if such a specification is required.

ignoring this angle and the *aerodynamic* error of ignoring the air velocity gradient between the hood edge and the ventilated process. In fact, the selection of the proper control velocity for use with these or similar equations may be much more difficult than the correct estimate of the face opening.

7. *Sidedraft or Backdraft Hoods*

The flow of air in this case is horizontal, preferably from the worker, across the source of contaminant and into the hood. Sidedraft hoods have the advantage of offering no overhead obstruction when parts must be moved about with cranes or hand hoists (Fig. 10). It is also easier to keep the worker in a clean-air zone than when he works under a canopy hood. Ventilation requirements are greater with sidedraft hoods than with canopy hoods whenever there is a natural tendency of the air to rise above a cooler surrounding atmosphere. Sidedraft hoods operate practically the same as booths if the hood can be located close to the source of dust or vapor (Fig. 11). If they must operate from a distance, they become nothing but an atmospheric "low spot" toward which air will flow from all directions, including the desired direction. As in the case of canopy hoods, we must visualize the probable "zone of escape" or route by which the air will try to escape with its contaminant. To counteract this tendency we must determine an effective "zone of influence" for the exhaust hood.

"Push-pull" systems are a novel variation of the sidedraft hood. On one side of the source of dust is placed a sidedraft exhaust hood. On the opposite side a device is placed to blow air across the dust source and into the exhaust hood. In practice, this method has the serious disadvantage that a blowing nozzle tends to remove the dust from an object that passes through the high-velocity air screen; consequently a greater exhaust volume must be used than if the system were "pull-pull" or exhaust on both sides of the process (Fig. 12).

[26a] J. M. Kane, *Foundry*, **66**, 30 (Jan., 1938).

Fig. 10. Sidedraft exhaust hood for casting shakeout (*courtesy Claude B. Schneible Co.*).

Fig. 11. Traveling shakeout grille with exhaust ventilation (*courtesy Wolverine Brass Works, Grand Rapids, Mich.*).

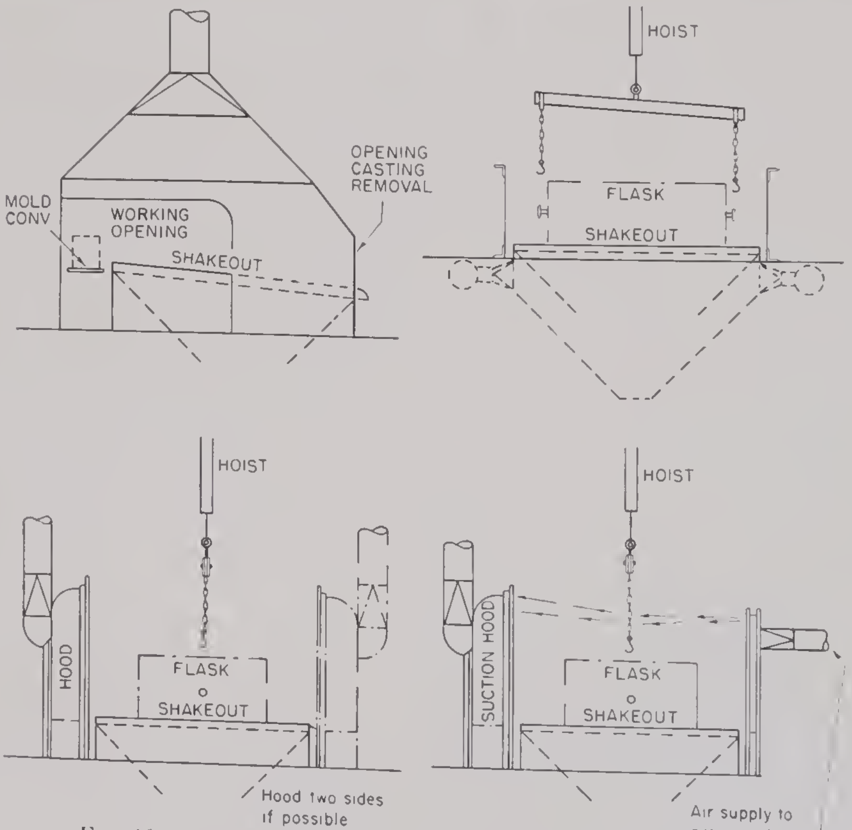


Fig. 12. Several methods of ventilating shakeout processes.[26a]

8. *Downdraft Hoods*

Hoods of this type draw the air downward across the process. They are most common in the form of perforated or grille-top tables and benches upon which the work is placed (Fig. 2), but have been used in very large sizes covering a substantial portion of a workroom floor. They have the advantage of minimum interference with the work, but are costly to install and are troublesome to maintain if large quantities of dust are handled. They are more successful in the large floor sizes if installed above the ground floor so that servicing can be done readily from the floor below the ventilated process. For dust handling, the downdraft hood may also be part of a hopper and conveyor mechanism for carrying off heavy dust particles not removed by the ventilating ducts.

A major disadvantage of the downdraft method is the trouble encountered with hot processes that create a strong thermal updraft opposing the air currents moving down into the hood. To succeed under such conditions the air velocity downward must be generously in excess of the thermal updraft velocity. Another problem is the inevitable obstruction created by the work as it is placed upon the grille or openwork of the downdraft hood. The solution is to provide a grille considerably larger than the product to permit the required amount of air to pass down alongside the work fast enough to oppose crossdrafts and thermal effects.

9. *Face Velocity*

"Face velocity" is not enough information for estimating air-flow requirements. It is necessary to visualize the probable boundaries of the zone in space through which contaminated air can move away from the updraft, sidedraft, or downdraft hood. The approximate surface area of this imaginary zone is then computed by plane, cylindrical, or spherical geometry, and multiplied by the best estimate of *controlling air velocity*. The hood *face velocity* is simply the result of its face area determined by mechanical considerations, and the total air flow to provide the required velocity toward or across the *zone of escape*. It is important to realize, as shown in Figure 6, that exhaust hoods draw air from all directions, unless the region of flow is predetermined by solid baffle plates, flanges, walls, or channels. Therefore, when the *sphere of influence* of an exhaust hood of any type is being estimated, *all* directions must be accounted for (*1*) as points from which air flow is desired, (*2*) as places where the air flow is prevented by solid obstructions, or (*3*) as points from which it is fully understood that air will flow wastefully, against the designer's wish.

10. *Slot Exhaust Ventilation for Tank Processes*

Figure 13 illustrates the slot or lateral-exhaust type of ventilation commonly applied to tanks for cleaning or degreasing, stripping, paint dipping, heat treating, anodizing, electroplating, and deplating. The air velocity into the exhaust slot is determined by the total quantity of air flow required to suppress or hold the contaminant within the tank, and the size of slot selected by mechanical considerations.

The *minimum* practical slot velocity for the design of Figure 13 is about 1000 l.f.m. in the interest of reasonably uniform distribution of air flow, when a single duct connection is used with slot extending around the tank. Lower velocities will give uniform distribution only when several duct connections can be made to the "draft box" or when the box or manifold is unusually large.

The *maximum* practical slot velocity is about 3000 l.f.m. in the interest of power economy, and minimum entrainment of mists or agitation of tank contents. Higher air velocities through very narrow slots *may* improve the uniformity of air

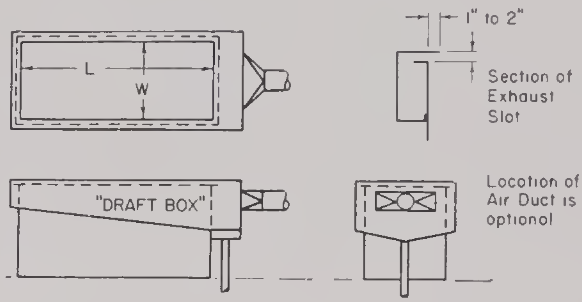


Fig. 13. Slot exhaust ventilation for tank processes. Slope draft box to drain for flushing purposes; provide drain pipe with water seal or trap deep enough to prevent air flow up through pipe. An alternate method of draft box design is extension to the floor to connect with ducts below floor level.

distribution around the tank when the mechanical design or construction of ductwork is not good, but they should not be used unless power cost is of no consequence, or unlimited exhaust fan capacity is available.

The quantity of air flow required is determined by the equation:

$$\text{c.f.m.} = (\text{velocity factor})\ (L)\ (W)$$

where c.f.m. = the total air flow in c.f.m., L = length of tank in feet, and W = width of tank in feet.

Velocity factors are suggested in Table 14. Brandt[27] correlated all available data on the ventilation of finishing tanks and concluded that an equation of the above form would define ventilation requirements for all kinds of tank processes. His general equation is $Q = KLWV$. The velocity factors in Table 14 combine K and V in a single numerical constant, which is warranted until further research is conducted to establish the best values for K and V in Brandt's equation. An important consideration in selecting the proper velocity factor for electroplating is electrode efficiency. The electrolytic efficiency at the cathode and anode determine the amount of gas evolved, which in turn determines the amount of mist generated at the liquid surface.[28] Failure to investigate this fact more carefully as it applies to operations in widely different plants, products, and platings is responsible for some of the discrepancies observed between ventilation rates initially specified and those actually required in full production.

[27] A. D. Brandt, *Heating, Piping, Air Conditioning*, **17**, 237 (May, 1945).

[28] W. Blum, *Health Hazards in the Electroplating Industry.* From the Proceedings of the University of Michigan In-Service Training Course on Environmental Controls for Industrial Processes. Univ. of Michigan, Ann Arbor, 1946.

TABLE 11

Air Velocity Factors for Tank Ventilation

Velocity factor c.f.m. sq. ft.	Process or application
50	Solvent or vapor degreaser (trichloroethylene)
100	Hot water rinsing tank (nuisance control)
120	Electroplating—Class I and II—ASA *Code Z9.1* (1941
150	Preferred for chromium electroplating
	Cyanide plating solutions giving off much gas or mist
	Muriatic acid (HCl) pickling
	Molten salt baths for heat-treating
	Aluminum anodizing
200	Electrolytic cleaning with sodium hydroxide
	Hot caustic or alkali cleaning or degreasing
	Boiling water solutions (steam and mist control)
250	Stripping with concentrated nitric acid
	Stripping with concentrated nitric and sulfuric acids
	Hot nitric hydrofluoric acid pickling
	Hot sulfuric acid pickling

11. Tailpipe Exhaust Systems for Internal-Combustion Engines

Figures 14 and 15 illustrate two methods of applying local exhaust to the tailpipes of automobiles and trucks for control of carbon monoxide and smoke in repair garages. The overhead system is favored for its ease of maintenance and simplicity of installation. It is avoided by some proprietors who desire to create the best possible appearance in their garage in keeping with the trend toward simplified and streamlined interior construction.

The underground system fulfills the desire to hide the ventilating equipment, and is highly effective when carefully designed for easy maintenance. Since dirt, water, oil, and gasoline all may collect in the underground main, provisions must be made for drainage and periodic cleaning. Because of the danger of accumulation of flammable liquids, design should be based on continuous operation of the exhaust fan with some air flowing through each section of the system at all times. The drain to the sewer or sump must be provided with a trap sufficiently high to prevent surge of water back into the exhaust-fan line as a result of the negative pressure created.

The air flow required at the end of the flexible conduits varies with the size of engine serviced, and is generally selected to be greater than the volume of exhaust gases discharged when the engine is operated at fairly high speed. The end of the flexible duct is slightly larger than the vehicle tailpipe to permit some room air to enter the system at this point. This prevents leakage and compensates for the variability in engine speed or displacement.

The following air-flow rates per flexible duct have given satisfactory control in many garages: automobiles and light trucks, 100 c.f.m.; heavy gasoline engine trucks, 200 c.f.m.; diesel engine trucks, 300 c.f.m. The high rate for diesel engines is due in part to the highly irritating nature of the combustion products. Air velocities

FIG. 14. Overhead tailpipe exhaust system for service garages (*courtesy Detroit Bureau of Industrial Hygiene*).

FIG. 15. Floor-type tailpipe exhaust system for service garages (*courtesy Kent-Moore Organization, Detroit*).

in the main ducts can be in the range of 1000–2000 l.f.m. Flexible branch ducts should be 2½ to 4 in. in diameter to avoid excessive velocity and air-flow resistance.

12. *Special or Irregular-Shaped Hoods*

The most familiar example of this group is the kind of hood installed on grinding, polishing, buffing, or sanding wheels and belts.[29] The shape is determined largely by the outlines or contours of the rotary device to be ventilated. These hoods should

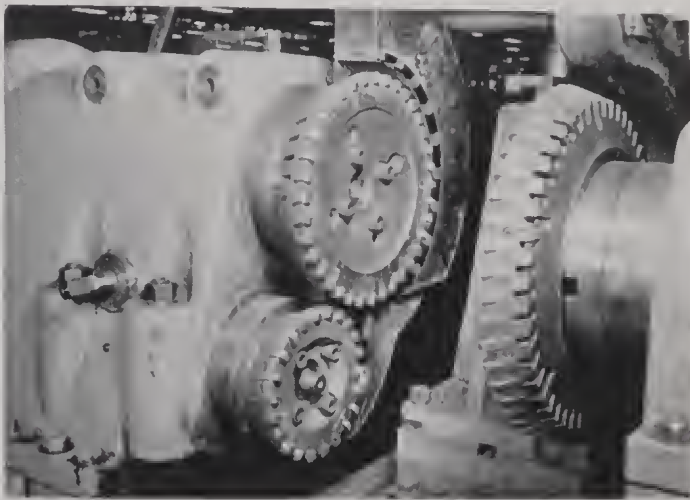


FIG. 16. Example of hoods for cast-iron milling operations (*courtesy Detroit Diesel Engine Division, General Motors Corporation*).

be custom-designed to enclose the dust, fume, vapor, or gas source as much as possible, and yet remain out of the operator's way so that he can do his work without discarding the exhaust hood as a "bad job."

Other examples are hoods for woodworking machines,[30, 31] textile machines,[32] conveyors and bagging stations,[33] pneumatic rock drills and stone-surfacing machines.[34–39] A few special types are illustrated in Figures 16, 17, and 18.

[29] "American Standards for Grinding, Polishing and Buffing Equipment Sanitation." *ASA-Z43.* Am. Standards Assoc., New York, 1941.

[30] J. L. Alden, *Design of Industrial Exhaust Systems.* Industrial Press, New York, 1939.

[31] Typical designs for exhaust hoods prepared by the Plan Examination Office, Div. Ind. Hyg., N. Y. State Dept. Labor.

[32] J. M. DallaValle, *Exhaust Hoods.* Industrial Press, New York, 1944.

[33] *Mill Mutual Fire Prevention Bureau (Chicago), Eng. Service Dept. Bull.* No. **DC-200A** 1943.

[34] W. C. L. Hemeon, *Heating & Ventilating* **37**, 41 (June, 1940); **37**, 54 (July, 1940).

[35] T. Hatch, H. Warren and G. S. Kelley, *J. Ind. Hyg. Toxicol.*, **14**, 246 (Sept., 1932).

[36] T. Hatch, J. W. Fehnel, H. Warren, and G. S. Kelley, *J. Ind. Hyg. Toxicol.*, **15**, 41 (Jan., 1933).

[37] T. Hatch, "Exhaust Ventilation in Wet Rock Drilling," *Ind. Bull., N. Y. Dept. Labor*, **16**, 389 (Oct., 1937).

[38] E. C. J. Urban, *J. Ind. Hyg. Toxicol.*, **21**, 57 (Mar., 1939).

[39] T. Hatch and W. B. Harris, "Requirements for Dust Control in Stone Cutting," *Ind. Bull., N. Y. Dept. Labor*, **18**, 379 (Dec., 1939).

Table 15 suggests ventilation rates for grinding, polishing, and buffing wheels. This schedule is based on the concept that the ventilation rate must depend on the quality of hood provided. Thus, if polishing or buffing wheels cannot be as completely enclosed as grinding wheels, larger volumes of air will be necessary to capture the generated dust and lint.

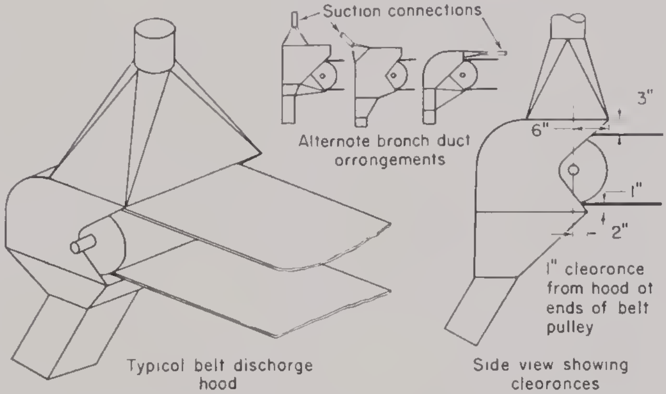


FIG. 17. Variation in design of hoods for conveyor-belt transfer stations (*courtesy Mill Mutual Fire Prevention Bureau, Chicago*).

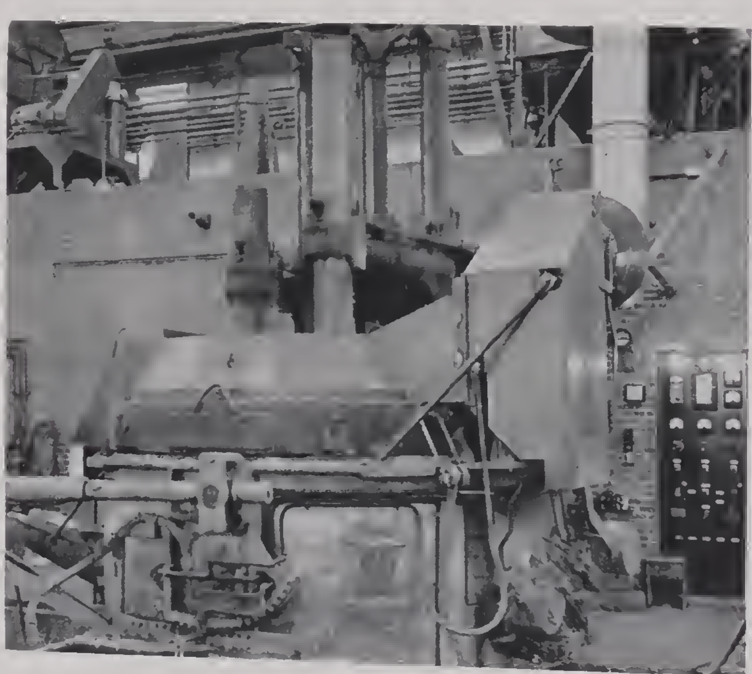


FIG. 18. Local exhaust hood for electric furnaces (*courtesy American Air Filter Co.*).

TABLE 15

Minimum Exhaust Ventilation for Grinding, Buffing, and Polishing Wheels[40]

Maximum wheel diam., inches[a]	Minimum air volumes, c.f.m.	
	Good wheel enclosure[b]	Poor wheel enclosure[c]
1 to 4	200	300
5 to 9	300	450
10 to 14	400	600
15 to 19	550	800
20 to 24	700	1000
25 to 29	900	1400
30 to 36	1200	1800

[a]Largest wheel than can be used within the exhaust hood.

[b]Not more than 25 per cent of wheel periphery and wheel sides exposed.

[c]Buffing and polishing wheels generally require air quantities listed under "Poor wheel enclosure."

Kane[41] has compiled a useful list of air flows representing good practice for control of certain dusty processes; Table 16 is adapted from his original tabulation.

TABLE 16

Volumes of Air Exhaust for Dust-Producing Equipment

Dust-producing equipment	Exhaust hood type	Air-flow requirements
Abrasive-blast rooms (sand, grit, or shot).	Tight enclosure with air inlets (usually in roof).	60–100 f.p.m. downdraft (long rooms of tunnel proportions 100 f.p.m. cross-draft). Exhaust volume should be sufficient to provide visibility for operator. Sand as abrasive, or castings with cores, or heavy molding sand deposits require highest range.
Abrasive-blast cabinets	Tight enclosure with access openings.	20 air changes per minute but not less than 500 f.p.m. through all openings.
Bagging machines.	Booth or enclosure (provide spillage hopper).	Paper bags, 100 c.f.m. per square foot open area. Cloth bags, 200 c.f.m. per square foot open area.
Barrels (for filling, or removing material).	Local hood 120 deg. around top of barrel.	Through 24-in. diam.—4-in. branch. Over 24-in. diam.—5-in. branch, at 3500 f.p.m.
Belt conveyors.	Hoods at transfer point.	Belt speeds less than 200 f.p.m.—350 c.f.m. per foot of belt width, but not less than 150 f.p.m. through open area. Belt speeds over 200 f.p.m.—500 c.f.m. per foot of belt width but not less than 200 f.p.m. through open area.
Belt wipers (may be required with high-speed belts).	Tight-fitting hood held against underside of belt.	200 c.f.m. per foot of belt width. Requires high hood suction and high conveying velocities. Mechanical brushing or wiping often used in conjunction with hood.
Bins (closed bin top).	Connect to bin top away from feed point.	150–200 f.p.m. through open area at feed points, but not less than 0.5 c.f.m. per cubic foot of bin capacity.

[40] Tentative Standard, Bur. Ind. Hyg., Detroit Dept. Health.

[41] J. M. Kane, *Heating & Ventilating*, **42**, 68 (Nov., 1945).

TABLE 16—*Concluded*

Dust-producing equipment	Exhaust hood type	Air-flow requirements
Bucket elevators	Tight casing required.	100 c.f.m. per square foot of elevator casing cross section. (Exhaust from elevator head.) To maintain indraft in casing only. Additional exhaust at elevator boot and discharge unless tight connections are employed.
Ceramics		
Dry Pan.	Local hoods.	See Mixer.
Dry Press.		Automatic feed, 1–5-in. diam. branch at die. Manual feed, 1–5-in. diam. branch at supply bin; 1–5-in. diam. branch at die. 3000 f.p.m. conveying velocity.
Fettling, brushing, sagger filling, and unloading.	Downdraft or side hood.	100–150 c.f.m. per square foot of plan area of dust-producing operation.
Grinders, swing frame.	Booth.	100–150 f.p.m. indraft through opening in booth face.
Grinders, portable and flexible shaft.	Downdraft grilles. Use side shields where possible.	Bench type, 200–400 c.f.m. per square foot of exhaust grille but not less than 150 c.f.m. per square foot of plan working area. Floor grille, 200–400 c.f.m. per square foot of exhaust grille but not less than 100 c.f.m. per square foot of plan working area.
Tumbling mills, hollow trunnion type.	Exhaust connection by manufacturer.	Use branch diameter same size as exhaust outlet. For round mills branch diameter should be one sixth diameter of mill; for square mills, branch diameter should be 1 in. plus one sixth side dimension of mill.
Mixer.	Enclosure.	100–200 f.p.m. through working and inspection openings. Where mixer causes pronounced agitation, use indraft velocities in the higher range listed.
Pharmaceuticals, coating pans.	Narrow side hood.	Through 16-in. opening, 200 c.f.m. Over 16 in. through 22 in., 300 c.f.m. Over 22 in. through 26 in., 400 c.f.m. Assumes no heated air supplied to coating pan. Increase exhaust volume by c.f.m. of heated air where supplied.
Shakeouts Foundry	Enclosure.	200 f.p.m. through all openings in enclosure; but not less than 200 c.f.m. per square foot of grate area.
	Side hood (use side shields whenever possible).	400–600 c.f.m. per square foot of shakeout grate area.
Screens Vibrating, flat deck.	Enclosure.	150–200 f.p.m. indraft through hood openings, but not less than 25–50 c.f.m. per square foot of screen area.
Cylindrical.	Enclosure.	100 c.f.m. per square foot of circular cross section but not less than 400 f.p.m. indraft through openings in enclosure.
Miscellaneous packaging machines, granulators, enclosed dust-producing units.	Complete enclosure.	100–400 f.p.m. indraft through inspection or working openings, but not less than 25 c.f.m. per square foot of enclosed plan area. Volume will normally be insufficient to prevent dust settling on floor and equipment within enclosure.
Packaging, weighing, container filling, inspection.	Booth.	50–150 c.f.m. per square foot of open-face area.
	Downdraft.	75–150 c.f.m. per square foot of dust-producing plan area.

C. VENTILATION IN THE MUNITIONS INDUSTRY

The control of air contaminants in the manufacture and handling of explosives and chemical warfare materials requires a thorough knowledge of the safety precautions to be observed, and their effect on exhaust system design. A report on this subject was prepared by Brandt and his associates during World War II and included in a *Manual of Industrial Hygiene* compiled by the United States Public Health Service.[42] As might be expected, a great many ventilation problems in the munitions industry are identical with those in peacetime manufacturing, and Brandt's compilation of specific engineering control measures arranged by operation is not limited to war-industry applications.

IV. Air-Cleaning Methods and Equipment

The design and application of dust collectors, gas scrubbers, vapor adsorbers, fume filters, and electrostatic precipitators have advanced rapidly in the past decade. The most recent development of a general nature is in the use of such devices to restore industrial air to a satisfactory quality for return to the workroom, thereby creating "artificial ventilation."

Air-cleaning devices also make it possible to improve the quality of outdoor air before it is supplied to rooms or buildings where a high degree of purity is required for either personal reasons or production control.

Inasmuch as numerous combinations of the basic methods of air cleaning are now appearing on the market, no attempt is made here to give detailed descriptions of all these arrangements since the design of any one of the major types of cleaners is becoming a highly developed specialty. It is more within the scope of this chapter to discuss the applications and limitations of commercially available air-cleaning equipment from the viewpoint of industrial health and safety.

A. SELECTION AND PERFORMANCE OF AIR CLEANERS

The great diversity in the chemical and physical properties of air contaminants created inside factory buildings is well known. That air cleaning devices have highly specialized attributes is not so well understood. Selection of the correct cleaner, when performance, economy, and flexibility must be balanced, is a problem that has disturbed many a designer who feels a responsibility for the final outcome of his efforts.

Table 17 summarizes the types and sizes of contaminants captured by the principal air cleaning processes. There are many possible and practical combinations. Recent developments in this field have concentrated on the skillful assembly of several kinds of cleaners in a single installation for the best compromise between initial cost, operating expense, maintenance cost and time, contaminant disposal, equipment life, and cleaning efficiency.

It is fundamental that the sequence of air cleaning should be from the least

[42] U.S. Public Health Service, *Manual of Industrial Hygiene and Medical Service in War Industries*. Saunders, Philadelphia, 1943.

TABLE 17

Type and Size of Contaminants Retained by Air Cleaners

Air-cleaning process	Contaminants retained in quantity	Particle size (μ) retained in quantity
Gravity settling chamber	Dust	Above 100
Large-diameter cyclone	Dust, large pollen	Above 30
Small-diameter cyclone	Dust, mist, pollen	Above 5
Spray washing or scrubbing with water	Dust, mist, pollen, spores, bacteria; soluble vapor or gas	Above 2 for insoluble particle
Froth or foam collector (water containing wetting agent)	Dust, mist, pollen, spores, bacteria; soluble vapor or gas	Above 1 for insoluble particle
Washing or scrubbing with reagent solution	Any reactive substance	Particulate or nonparticulate
Water condensation collector	Any particulate substance	Below 10 (light loading)
High-velocity impingement in liquid (10,000–20,000 l.f.m.)	Dust, fume, mist, pollen, spores, bacteria; soluble vapor or gas	Above 0.1 for insoluble particle
Low-velocity impingement in air, or high velocity filtering (100–500 l.f.m.)	Dust, mist, pollen, spores, bacteria	Above 5 (very light loading below 1 grain/1000 cu. ft.)
Low-velocity filtering (1–5 l.f.m.)	Dust, fume, mist, pollen, spores, bacteria	Above 0.5 (loading up to 10 grains/cu. ft.)
Low-voltage electric precipitation (at 100–500 l.f.m. and 10,000–15,000 v.)	Any particulate substance (solid or liquid)	0.01–10 (light loading below 0.1 grain/cu. ft.)
High-voltage electric precipitation (Cottrell) (50,000–100,000 v.)	Any particulate substance	Up to 100 (heavy loading)
Thermal precipitation	Any particulate substance	0.01–10 (very light loading)
Ultrasonic flocculation	Any particulate substance	Dependent upon vibration frequency, intensity, duration
Adsorption (activated carbon, silica gel, alumina)	Vapor or gas	....
Absorption with dry chemical granules	Vapor or gas	....

effective, or primary separators, to the most effective units from the standpoint of fine-particle removal. The number of stages or different types of collectors provided in the same system depends upon the quantity and diversity of material in the air stream, and the degree of cleanliness demanded at the point of discharge. It is very difficult to design a single-stage dust collector that will take in air with very heavy "dust loading" from 1 to 100 μ in size, and discharge it with a physiologically permissible concentration of dust from 1–10 μ in size. On the other hand, it is relatively easy for many contemporary collectors to perform at 99 per cent efficiency if they are rated only according to the *weight* of dust removed from the air.

In a competitive market where percentage efficiency is so often cited, the emphasis is likely to be on the quantity of dust *retained* by the collector, rather than the quantity *discharged* with the air. In the field of occupational disease prevention,

the latter concept for the appraisal of air cleaners is essential whenever there is a demand for recirculation to save heat in the wintertime, or to maintain precision control of temperature and humidity.

Furthermore, collection efficiency is often carelessly expressed by both user and designer without reference to the size of contaminating particles. It is similar to specifying the volume of air flow produced by a ventilating fan without mentioning the resistance against which this volume is moved.

Anyone who has followed the trends of cleaning-equipment design surely realizes that standardization of quality and efficiency are not yet effectively demanded by all consumers. The brief history of the small unit dust collectors now on the market is ample evidence that product development may wander aimlessly unless the customer has positive methods of checking his purchase against intelligent specifications that tell the manufacturer just what performance he must deliver.

B. TYPES OF AIR CLEANERS

Four basic methods of air cleaning are now in use, and they are reviewed here in the following order: (*1*) cyclones, (*2*) washers, (*3*) filters, and (*4*) electric precipitators.

1. Centrifugal and Dynamic Collectors: Cyclones and Rotoclones

Cyclones operate by centrifugal force. They might also be given the name "air centrifuge." The dust particle within the collector is driven to the outer boundary of the rotating air stream where it can slow down in the lower-velocity air film next to the wall of the cyclone, and slide down by gravity to the conical hopper that forms the base of the collector.

Large particles do not require high velocities or sharp curvatures to throw them from the air stream, and hence they can be separated in a large-diameter cyclone. The removal of very small dust particles has become a highly competitive field for air cleaning equipment, and the manufacturers of cyclones have created the small-diameter, high-velocity, multiple-unit collector for competition with filters and wet collectors.

High velocities through cyclones mean high-pressure losses, and this accounts for the statement sometimes made that "the greater the pressure drop, the higher the collecting efficiency." Removal of small dust particles of the order of 5 μ may require pressure drops across a small-diameter, multiple-unit cyclone of as much as 10 in. of water. Pressure drop is directly related to the velocity of air entering the collector. Differences in size, design, and velocity cause the pressure consumption to vary from about 1 to 3 velocity heads.[43–45]

The higher efficiency of cyclones of smaller diameter makes it necessary to be

[43] Cyclone Collectors. Mill Mutual Fire Prevention Bureau (Chicago), *Eng Service Dept. Bull.* No. *DC-250* (1942).

[44] "Dust Collecting Systems Adapted for Use in Connection with the Granite Cutting Industry," *N. Y. Dept. Labor, Special Bull.* No. **128** (1924).

[45] C. B. Shepherd and C. E. Lapple, *Ind. Eng. Chem.*, **32**, 1246 (Sept., 1940).

very cautious in observing the demonstration of cyclone efficiency by a small model of large equipment. The particle-size efficiency (*differential efficiency* or *fractional efficiency*) of large cyclones cannot be assumed to be the same as geometrically similar small models unless the air velocities in the models have been correspondingly reduced to offset the advantage of sharp curvature. Reliable demonstrations of performance are conducted preferably with full-scale equipment against the actual dust produced by the prospective customer's process. Sample dust transported to a testing laboratory is subject to question when the method of sample collection eliminates or fails to retain microscopic dust of the order of 1–5 μ.

Dynamic precipitators or Rotoclones (trade name used by American Air Filter Company) combine a centrifugal fan with cyclonic precipitation and are used either dry or wet. Their fractional efficiency lies somewhere between that of large- and of small-diameter cyclones. Vibration and high air velocity tend to keep the very fine particles in suspension, and secondary filtration collectors are generally applied when air is recirculated to the workroom.

2. Wet Collectors: Spray Washers, Scrubbers, and Condensers

Man instinctively considers water to be an effective air-cleaning substance, no doubt from his impressions of outdoor rain-water dust control. If all man-made wet dust collectors took full advantage of the condensation principle essential to outdoor precipitation, their performance probably would be enhanced.

The designer of wet collectors is confronted by endless patents on the use of water for dust control that have accumulated for generations without uncovering or revealing the ideal or best method of combining air and water to capture particulate matter. The truth is that no single design can be called a universal collector, and reputable manufacturers make no such claim.

Some designers maintain that the closer the air is brought to saturation, while it passes through a wet collector, the better will be the collecting efficiency. Perhaps even more important is to have the air nearly saturated before entering the collector, in order to obtain the longest possible operation of the "cloud chamber" effect. It has long been observed that application of wet collection to high-temperature air streams, where use can be made of evaporative cooling and condensation, produces some surprisingly high cleaning efficiencies with a minimum of equipment. The high-pressure fog nozzle creating an essentially supersaturated atmosphere seems to have attractive possibilities in the field of dust collection.

It is evident that the physical and chemical properties of the substance to be collected must have very direct bearing upon the success of wet collection. Materials that are already moist or hygroscopic, easily wetted, free of adsorbed air, or readily soluble, are the kinds for which wet collectors are indicated. The chemical-process industries use a large variety of wet methods for collecting products or by-products, and the reverse process of aeration for removing valuable chemicals from liquids.

Substances that are readily soluble in water and those that are hygroscopic cannot be handled successfully in dry collectors. In fact they tend to cake and foul the entire ductwork of exhaust systems. Even materials like iron dust will gradually crust or cake within the system when relative humidities are much above 30 per cent, possibly owing to the merging of iron particles during oxidation.

Hygroscopic materials are technically those that remove moisture from the air, even at low humidities; in fact, they can be used to obtain low humidities in chemical operations and in air conditioning. Actually, from the viewpoint of the ventilating engineer, any material, whether it be readily soluble or truly hygroscopic, is loosely classified as hygroscopic when it tends to cake inside exhaust or dust-collecting equipment under the influence of normal atmospheric humidities. Possibly all chemical compounds that are easily soluble in water should be collected by wet methods in preference to dry, to avoid the difficulty of caking.

Combustible dusts, as from the grinding of magnesium and the manufacture of explosives, were successfully controlled by wet collection during World War II.[46]

3. *Filters: Cloth, Felt, Paper, Asbestos, Glass, and Metal*

Filters are porous substances of uniform or variable density, either shallow or deep, through which air is forced so that dust can be stopped by impingement on dry or viscous surfaces, by static attraction, or by screening. When made with variable density or porosity, the direction of air flow is from the coarse to the fine sections of the filter medium. This flow helps to achieve more complete dust penetration in the interest of longer filter life, lower air-flow resistance, and higher efficiency. Filters are characterized by a tendency toward increased resistance as the deposit of dust or fume progresses. This condition has led to the development of mechanized or self-cleaning filter devices to hold the resistance within reasonable limits. "Throw-away" or "renewable" filters are discarded when the air-flow resistance becomes too great. Most large industrial installations are provided with periodic, manual, or automatic "rapping" machinery to dislodge the filter-cake and restore the initial low resistance to air flow. *Manual* shakedown requires some form of manometric or pressure-indicating instrument connected across the filter as a warning to clean the filter before ventilation of the dusty process is seriously impaired.

Resistance through filters used for light duty in air conditioning ranges from 0.05 to 0.5 in. of water at velocities of from 100 to 500 l.f.m. Industrial dust filters, known as *cloth arresters*, may operate at resistances of from 1 to 5 in. of water at velocities of from 0.5 to 10 l.f.m.

Williams, Hatch, and Greenburg[47] developed an equation by which the required area of industrial cloth filters may be computed in terms of an experimentally determined coefficient for a specific dust, the dust concentration in the air approach-

[46] J. M. Kane, *American Artisan* (Jan., 1945).

[47] C. E. Williams, T. Hatch, and L. Greenburg, *Heating, Piping, Air Conditioning*, 12, 259 (Apr., 1940).

ing the filter, the filtering velocity, and the maximum permissible rise in filter resistance. Hemeon[48] studied the operating characteristics of commercial cloth filters handling granite dust, and presented his formula for estimating the pressure drop based on filtration velocity, dust accumulated on the cloth, initial resistance at 1 l.f.m. filtration velocity, and resistance at 1 l.f.m. with a loading of 1 oz. of dust per square foot of cloth. Madison[49] has assembled data on pressure loss for various kinds of cloth filter materials. Rowley and Jordan[50, 51] have conducted extensive research on the properties and performance of filters of the type commonly employed in commercial and residential air conditioning.

4. Electrostatic Precipitators

Electrostatic precipitation is the method of choice for highly efficient removal of liquid and solid particles in the range of 0.1 to 10 μ. In comparison with very low velocity filtration through dense fabrics, it has the advantages of low or negligible resistance to air flow, possibility of construction for use at high temperatures, smaller space requirement, and lower cost of maintenance and operation. The early Cottrell precipitator was designed to operate at voltages of from 50,000 to 100,000 for chemical plant fume and mist collection, power plant fly-ash and smoke retention, and metallurgical dust and fume recovery. The generation of substantial amounts of ozone prevented the use of these high voltages in air conditioning.

The low-voltage precipitators (10,000 to 15,000) developed for use in residential, commercial, and industrial-process air cleaning, are not intended for operation against high dust concentrations. Consequently, it is current practice to install one or more stages of dry or viscous separation ahead of the precipitator when the contamination before cleaning is more than about 0.1 grain per cubic foot of air. Precleaning is likewise desirable if large particles may occasionally enter the unit and short-circuit the plates.

In operation, the contaminated air is first passed through a high-tension electrostatic field where the particles of dust, fume, smoke, mist, pollen, or microorganisms receive electric charges. As the air moves into the precipitating section, the particles are attracted to collector plates oppositely charged, and remain there until scraped off, removed by vibration, or washed down for disposal; or if the plates are dry, the neutralized dust cake builds up to a point at which friction will no longer keep it from dropping into the base of the collector. One commercial design combines electrostatic precipitation with automatic viscous filtration, whereby the collector plates are continuously cleaned and reoiled by slowly passing through an oil bath and sludge chamber at the base of the machine. Care must be taken not to use electrostatic precipitators against highly combustible dust, nor in the presence

[48] W. C. L. Hemeon, *Heating & Ventilating*, **37**, 41 (Aug., 1940).
[49] R. D. Madison, *Fan Engineering*. 5th ed., Buffalo Forge Co., 1948.
[50] F. B. Rowley and R. C. Jordan, *Trans. ASHVE*, **45**, 339 (1939).
[51] F. B. Rowley and R. C. Jordan, *Trans. ASHVE*, **47**, 391 (1941).

of highly flammable vapors that might accidentally reach their lower explosive limit in air.

C. RECIRCULATION FROM AIR CLEANERS

Most regulatory authorities do not permit recirculation until it is definitely proved by test or experience that the air cleaner in question can reduce the contamination in the discharged air well below the "maximum allowable concentration" established under their jurisdiction. When permitted, the proportion of recirculated air in the total air flow depends upon the quality and type of cleaner, the degree of contamination, and the relative hazard of the contaminant from the standpoint of health, fire, or explosion.

Dusts from the operation of grinding on steel or iron products with silicon-carbide or aluminum-oxide wheels are rated as "nuisance" dusts by most authorities, and are successfully retained by some types of unit collectors now on the market. One state has investigated the operating characteristics of such collectors.

Whether the proposed saving in air-borne heat is sufficient to justify the expense of air cleaning for recirculation is a matter for careful cost accounting or analysis (see pages 288–291).

D. AIR BACTERIA CONTROL

The current status of this subject is a controversy between two speculative viewpoints that await confirmation in the results of research now in progress. On the one hand, the proponents of air sterilization hold that control of air-borne organisms should be practiced in a measure comparable at least with the control of microorganisms in potable water supplies. Some even contend that control should be more rigid for air-borne organisms in view of the intimate contact between the atmospheric environment and the respiratory surfaces.

The opposing viewpoint questions the feasibility, necessity, and wisdom of maintaining a nearly sterile atmosphere as a means of controlling communicable respiratory disease. On feasibility, it is pointed out that no one who is not an invalid or bedridden can be given a bacterially controlled atmosphere 24 hours of the day. On necessity, the importance of moderate concentrations of air bacteria as a source of disease is seriously questioned. On wisdom, some physicians raise the question of the part played by bacteria in the air of public and private spaces as a means of gradually building up the body's resistance to myriads of air-borne organisms.

For those physicians, bacteriologists, physicists, public health workers, engineers, and hospital personnel who wish to study the value of bacteria control, there are highly effective methods available. These include ultraviolet radiation, both inside the ducts of ventilating systems, and in occupied spaces;[52, 53] germicidal mists, vapors, or gases, likewise used in air-supply equipment, or in rooms;[54, 55] and the

[52] W. F. Wells, *Trans. ASHVE*, **50**, 361 (1944).

[53] L. J. Buttolph, *Heating, Piping, Air Conditioning*, **17**, 282 (May, 1945) (*ASHVE J. Section*).

[54] B. H. Jennings and E. Bigg, *Am. J. Pub. Health*, **34**, 477 (May, 1944).

[55] B. H. Jennings, E. Bigg, and F. C. W. Olson, *Trans. ASHVE*, **50**, 343 (1944).

conventional air-cleaning methods of filtration and electric precipitation.[56, 57] Filtration must be conducted at relatively low velocity to be effective against bacteria.

Wells[58] applied air sterilization to a few Philadelphia and Germantown schools during 1940 and 1941, and offered the results as evidence of the effectiveness of ultraviolet radiation in controlling childhood epidemics. Recent studies of this type have done much to stimulate controversial interest in air bacteria control for public buildings and vehicles where large numbers of people are in close atmospheric contact with one another for extended periods of time.

V. Aeromotive Methods and Equipment

The forces available for ventilation are readily divided into (*1*) natural, and (*2*) mechanical, as in the discussion of general ventilation.

A. NATURAL AEROMOTIVE FORCES

Natural ventilation may be (*1*) gravity, motivated by the thermal forces of convection, or (*2*) anemotive, created by wind pressure. These two natural forces operate together in most cases, and a study of their effects has led to the concept of the "neutral zone" in thermal ventilation, modified by experimentally verified wind-pressure corrections.

Emswiler and Randall[59] give the following analysis of the combined action of wind and thermal forces in producing air flow through a building:

"Even without any wind, a difference of temperature inside and outside will cause the pressure state inside to be less than that outside at the ground, and greater near the roof, and inflow will occur at lower windows and outflow at upper windows. If the building is tall and open throughout from bottom to top, or if arranged in stories in free communication from one to another, and if the temperature difference is great, the pressure difference created at a point near the ground and also at a point near the roof may be considerable. Thus, in a building 200 ft. high with 70° F. difference in temperature, this force alone causing inflow at the ground and outflow at the top, may easily exceed 0.20 in. of water, which is the equivalent of a twenty-mile wind. If the building is multiple storied and there is absolutely no communication between stories, then the force of temperature difference is effectually nullified, or rather reduced to an amount proportional to the height of a single story. However, there is always some communication by means of stairs and otherwise, so that the force of temperature difference is always operative in some degree.

"If the wind blows against a window of a building that is tightly sealed at all other points of possible ingress or egress of air, there will be no continuous infiltration at the window, because the temporary excess of pressure outside will soon be equalized by a momentary inflow. If the building has an outlet of exactly the same area as the presumed infiltration area of the window, and this outlet opens into a region of neutral pressure, then the pressure in the room will be half as much as that produced by the wind outside. Infiltration will take place through the window, but with only half the force of the wind pressure. Something like this is what occurs in any building. Whatever air

[56] ASHVE *Guide*, 1948, chapters on air cleaning and air conditioning in the treatment of disease.

[57] J. M. DallaValle, *Heating & Ventilating*, **41**, 57 (May, 1944).

[58] W. F. Wells, *Am. J. Pub. Health*, **33**, 1436 (Dec., 1943).

[59] J. E. Emswiler and W. C. Randall, *Trans. ASHVE*, **34**, 527 (1928).

gets in at inflow points must escape somewhere else. In order to force the air out, there must be a greater pressure inside somewhere than that which prevails immediately outside. The inside pressure automatically assumes a value that will give the necessary head for outflow through openings available, *so that the outflow quantity always balances the inflow*" (*italics ours*).

1. *Wind Direction, Velocity, and Pressure*

Few locations in the United States have what is actually a "prevailing" wind direction, or one from which the wind blows most of the time. Not over 5 per cent of the land receives wind from one general direction as much as 50 per cent of the time. Wind data collected by the Weather Bureau at stations located on the tops of high buildings cannot be taken as representative of ground conditions throughout the entire area. The observing stations in large cities are so located in order to sample stratum of air that is unaffected by turbulence generated by surrounding structures.

The velocities of the winds at these elevated locations are higher than ground values would be if no obstructions existed. For those design problems where the minimum daylong wind velocity determines the quantity of natural ventilation to be expected, values about one half the indicated seasonal average velocities should be chosen.[60] Average wind velocities throughout the United States range from 5 to 15 m.p.h. for all seasons of the year.[61]

In cases where an occasional gust of wind, or the pressure of high wind velocities for a few hours of a day would create dangerous reduction of ventilation on a system handling irritating or hazardous gases, vapors, or dusts, the ventilator must be protected against such pressures. It is evident that a substantial wind pressure applied to the side of a building in which a fan is mounted may seriously reduce the volume of air moved and may even reverse the direction of flow when the fan is not

TABLE 18

Wind Velocity Pressure

Miles per hour (m.p.h.)	Linear feet per minute (l.f.m.)	Velocity pressure inches of water (V.P.)[a]	Visible or physical effects
1	88	0.0005	Smoke rises vertically
2	176	0.0019	Direction of wind shown by smoke drift
3	264	0.0044	Moderate walking speed
4	352	0.0077	Fast walking speed
5	440	0.012	Wind felt on face; leaves rustle
10	880	0.048	Wind extends light flag
15	1320	0.11	Raises dust and loose paper
20	1760	0.19	Crested wavelets form on inland water
25	2200	0.30	Umbrellas used with difficulty
30	2640	0.44	Whole trees in motion
35	3080	0.59	Difficulty walking against wind
40	3520	0.77	Breaks twigs off trees
50	4400	1.2	Slight structural damage to buildings
60	5280	1.7	Considerable structural damage

[a] $V.P. = (l.f.m./4000)^2$. $V.P. = 0.00048\ (m.p.h.)^2$.

[60] ASHVE *Guide*, 1948.

[61] J. C. Albright, *Summer Weather Data*. The Marley Co., Kansas City, Kansas, 1939.

creating a high static pressure. Some type of baffle, "windbreaker," or automatic damper should be provided, or the fan should be selected for a higher static pressure to compensate for reasonable wind pressures above the average. Table 18 assembles some of the data needed for consideration of the wind velocity-pressure factor.

2. Roof Ventilators

Recent application of motor-driven axial and centrifugal fans to stacks or vertical ducts for general ventilation is effective testimony that wind and heat-driven devices are not sufficiently dependable for the great majority of industrial applications. Wind velocities must be high and temperature differences large to permit the consistent and reliable operation of ventilators utilizing natural forces.

An effective combination for reliable ventilation is the use of a pivoted or oscillating roof ventilator with an axial-flow fan mounted in the base, as shown in Figure 19. This assures a positive, predictable flow of air; provides the fan with a discharge outlet that locates itself downstream with respect to the wind; and gives the fan substantial assistance instead of opposition at high wind velocities from any direction.

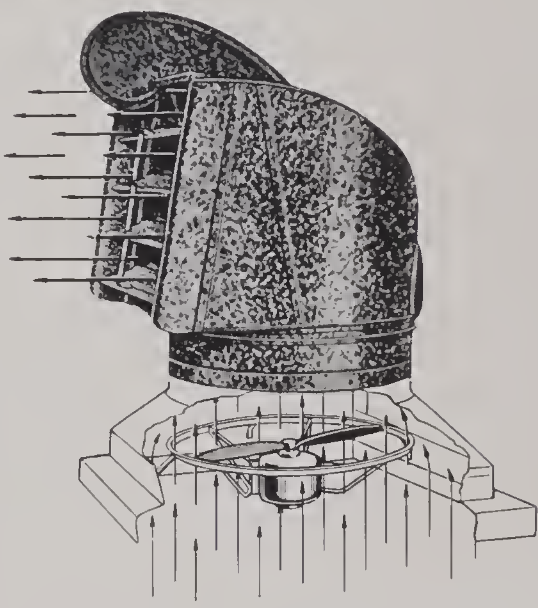


FIG. 19. Pivoted roof ventilator combined with axial-flow fan (*courtesy The Swartwout Company, Cleveland*).

For those who need to estimate the velocity of air flow through stationary "gravity" ventilators, an *approximate* empirical formula is available in terms of temperature difference in degrees F., height in feet between inlet and outlet, and moderate wind velocity in m.p.h. To apply this formula, the air-inlet area must not be less at any point than the stack or ventilator throat area.

$$(\text{l.f.m.}) = 10\sqrt{(\text{height})\,(\text{temp. diff.}) + 16\,(\text{m.p.h.})^2}$$

This equation ignores the variability in friction, turbulence, and entrance and discharge losses by assuming that the ventilator is about 50 per cent efficient in its utilization of the combined forces of wind and heat. It is not suitable for the accurate study of comparative performance of commercial ventilators, but is introduced here as a means to demonstrate that velocities through stationary roof ventilators seldom exceed 500 l.f.m. Only at the high temperatures available with hot processes, or in power plant stacks, can high updraft velocities be anticipated.

Examples in the use of the above formula are: (*1*) at a height of 30 ft., temperature difference of 30° F., and zero wind velocity, the stack velocity is 300 l.f.m.; (*2*) at 10 m.p.h. wind and no temperature difference, the stack velocity is 400 l.f.m.; (*3*) at 30 ft. height, 30° F. differential, and 10 m.p.h. wind, the stack velocity is 500 l.f.m.; and (*4*) at 50 ft. height, 50° F. differential, and zero wind velocity, the stack velocity is 500 l.f.m.

3. High-Temperature Stacks

The theoretical static pressure or "draft" developed between two columns of air at substantial temperature differences can be computed from the following simplified and approximate formula:

$$(\text{S.P. in inches of water}) = \frac{(\text{height in feet})\ (\text{temp. difference °F.})}{32{,}000 + 70\ (\text{stack gas temp. °F.})}$$

Ordinarily only about 60 to 80 per cent of this theoretical draft is available, depending upon the stack diameter, nature of flue-gas entrance, and the velocity of air or gas flow.

For *available draft* in chimneys, where the flue-gas temperature is about 500° F. above the outdoor temperature, an approximate figure of 0.005 in. per foot of stack height is sometimes used.[62] The American Foundrymen's Code[63] makes the following provisions with respect to "Chimney Exhausts":

Any process or operation which is dependent on the combustion of fuels in its operation, and which can be so enclosed at all times so that there is no leakage of harmful gases or matter into the room atmosphere, may be exhausted to the outside by means of a natural draft chimney—provided the chimney temperature is *at least 300° F.*, and the chimney can be attached directly to the equipment.

Chemists and laboratory technicians have been aware, for many years, of the method of creating ventilation for their hoods by placing a gas burner at the base of the ventilating flue. They are also aware of the marked improvement in laboratory ventilation when this gravity or thermal type aeromotive force is replaced by a reliable motor-driven fan.

B. MECHANICAL AEROMOTIVE FORCES

1. Fans: Blowers and Exhausters

Rotating devices for the movement of air in either general or local ventilating systems are of two fundamental types. They are conveniently classified as either (*a*) *axial flow*, which includes long-blade propeller and disk fans, and very short-blade high-pressure axial fans; or (*b*) *radial flow*, or centrifugal fans, with the revolving element made of radial blades fastened to a central hub, or circumferential

[62] R. D. Madison, *Fan Engineering*. 5th ed., Buffalo Forge Co., 1948.

[63] *Tentative Recommended Good Practice Code and Handbook on the Fundamentals of Design, Construction, Operation and Maintenance of Exhaust Systems*, Am. Foundrymen's Assoc., Chicago, 1938.

blades shaped to curve forward or backward with respect to the direction of rotation, and supported with a rim or disk fastened to the central hub (see manufacturers' catalogs for illustrations).

It is very important for those who inspect and test mechanical ventilating systems to know that axial and centrifugal fans may be further designated according to the effect that direction of rotation has on the direction of air flow. Reversing the rotation of any axial-flow fan or disk will reverse the direction of air flow through it, inasmuch as flow parallel to the axis of rotation, as an "air screw," is essential for membership in this class. However, the flow of air through a centrifugal device can be only radial, or from the center outward. This means that its direction of rotation does not determine the direction of air flow, but simply affects the quality of its performance. Consequently, the direction of air flow through a centrifugal exhauster or blower *cannot* be used as a remote or distant indication of its direction of rotation. Reverse flow through this type of fan means either (*a*) that it is not operating, or (*b*) that it is subjected to external pressures greater than it can develop at its operating speed. The second statement, of course, applies likewise to axial-flow fans.

The high-efficiency axial-flow fan is a recent addition to the general class of air movers commonly known as "propeller fans." The term "axial flow," in fact, was not used extensively until the characteristic large-hub, short-blade fan emerged from the manufacturer's laboratories under pressure of space-saving specifications formulated during World War II. Heath and Criqui[64] have made the following interesting appraisal of the advancement in axial-flow fan design and manufacture: ". . . it might be said that the true axial-flow fan was born in the aeronautical research laboratory, received its basic training in the Navy, and is ready to join the industrial army."

(*a*) *Axial-flow or spiral-flow fan characteristics* (air flow *does* reverse when rotation is reversed).

(*1*) TYPE: *long blade* propeller or disk on small hub; with or without circumferential support.
DUTY: large volume, low pressure; best as "free flow" or low, stable resistance.
POWER: *maximum* horsepower at zero air delivery with maximum resistance; power gradually falling as resistance decreases and air volume increases (this relationship might reverse at a small unstable section of the power-volume curve).
EFFICIENCY: 30–40 per cent at optimum performance.

(*2*) TYPE: *short blade*, airfoil design with large streamlined hub, no circumferential support, designed especially for use within cylindrical ducts; control of power-pressure curve stability obtained by varying blade angles ("low," "medium," or "high" angle blades).
DUTY: large volume, medium or high pressure; freedom of choice for position of mounting; potentially quieter than propeller or disk when operated near maximum air delivery; useful where installation space is at a premium, as on ships.
POWER: *maximum* horsepower at zero delivery, but characterized by less difference between zero and maximum flow horsepower than for other fan types.
EFFICIENCY: 50–70 per cent at optimum performance; higher efficiency due to airfoil design, guide vanes or "straighteners," and precision blade-tip clearances.

[64] W. R. Heath and A. E. Criqui, *Trans. ASHVE*, **50**, 197 (1944).

(*b*) *Centrifugal or radial-flow fan characteristics* (air flow *does not* reverse when rotation is reversed).

(*1*) TYPE: *forward curve blade* in "squirrel cage" or circumferential support; blades usually wide and shallow.
DUTY: large volume, low to medium pressure; quiet for low-speed operation.
POWER: *minimum* horsepower at zero air delivery; power continuously rising with decreased resistance; *maximum* horsepower at "free delivery" with minimum resistance; this type has greatest danger of burning out motor if system resistance is suddenly decreased or is substantially less than anticipated in design.
EFFICIENCY: 50–70 per cent at optimum performance.

(*2*) TYPE: *backward curve blade* in "squirrel cage" or circumferential support; blades wide and shallow; also may be backwardly inclined *straight* "steel plate" blade for heavy duty or pneumatic conveying.
DUTY: large volume, medium to high pressure, with "nonoverloading" feature.
POWER: *minimum* horsepower at zero air delivery; *maximum* horsepower near maximum air delivery, and near point of maximum efficiency.
EFFICIENCY: 60–75 per cent at optimum performance.

(*3*) TYPE: *"S" curve blade,* outer section curved backward, inner section curved forward with respect to direction of rotation; with circumferential support or "squirrel cage."
DUTY: large volume, medium to high pressure; nonoverloading; relatively low noise level for high-speed operation.
POWER: *minimum* horsepower at zero delivery; *maximum* horsepower near maximum delivery and maximum efficiency.
EFFICIENCY: 65–75 per cent at optimum performance.

(*4*) TYPE: *straight radial blade* or "paddle wheel" with either a "spider," disk, cone or circumferential ring support; blades often narrow and deep in a narrow, large diameter scroll.
DUTY: small to medium volume, with medium to high pressure; suitable for conveying shavings, fibers or sticky materials; high suction for vacuum cleaning; inherently noisy at high-speed, high-pressure duty.
POWER: *minimum* horsepower at zero delivery; *maximum* horsepower at maximum or "free" delivery.
EFFICIENCY: 50–60 per cent at optimum performance.

(*c*) *Special wheels or rotors for centrifugal fans.* A great many styles of centrifugal wheels are manufactured to accommodate the wide range of supply and exhaust ventilating and pneumatic conveying applications. They can be made of almost any rigid material, to: (*1*) resist abrasion, (*2*) minimize corrosion, (*3*) prevent sparking, (*4*) avoid plugging, (*5*) minimize noise, (*6*) limit horsepower, (*7*) resist fire, (*8*) handle high-temperature air, (*9*) reduce vibration, and (*10*) facilitate cleaning. This makes it evident that there is danger of false economy in the purchase of cheap fans and blowers for exhausting and conveying, inasmuch as the motive power is the heart of the air-handling system.

(*d*) *Fan selection.* The following check list indicates the amount of care required in the proper selection of centrifugal- or axial-flow fans. Items 1 and 2 are essential in every case, while in most cases many of the additional items must be given some thought: (*1*) c.f.m. of air to be moved; (*2*) static pressure against which this air must be moved; (*3*) permissible noise level, or noise character of the environ-

ment; (*4*) whether constant or variable speed of operation is expected; (*5*) type of motive power (AC, DC, compressed air, or heat engine); (*6*) direct or belt driven, and whether drive must be protected against air contaminants, heat, or excessive moisture; (*7*) kind of contaminants in air to pass through fan; (*8*) quantity of contaminants in air to pass through fan; (*9*) contaminants in the atmosphere *surrounding* the fan and motor, including potential explosion or fire hazard; (*10*) temperature of air or gases to pass *through* fan; (*11*) temperature of atmosphere *surrounding* fan and motor; (*12*) possibility of condensation within fan housing or scroll; (*13*) whether to be located before or after air-cleaning equipment; (*14*) size and shape of available space; (*15*) correct discharge direction for centrifugal fan to avoid unnecessary bends in ductwork.

(*e*) *Fan laws.* These relationships or physical laws apply when a given fan and ventilating system are operated together under variable conditions of fan speed and air density:

Variable fan speed—constant air density.

(*1*) Air volume (c.f.m.) varies directly with fan speed (r.p.m.).
(*2*) Static, velocity, and total pressures (S.P., V.P., T.P.) vary directly with the square of fan speed $(\text{r.p.m.})^2$.
(*3*) Horsepower (H.P.) varies directly with the cube of the fan speed $(\text{r.p.m.})^3$.

Constant fan speed—variable air density

(*4*) Air volume (c.f.m.) remains constant as air density varies.
(*5*) Static, velocity, and total pressures (S.P., V.P., T.P.) vary directly with air density (D.A.).
(*6*) Horsepower (H.P.) varies directly with air density (D.A.).

Constant weight of air delivered.

(*7*) Fan speed (r.p.m.) varies inversely with air density (1/D.A.).
(*8*) Static, velocity, and total pressures (S.P., V.P., T.P.) vary inversely with air density (1/D.A.).
(*9*) Horsepower (H.P.) varies inversely with the square of air density $(1/\text{D.A.}^2)$.

(*f*) *Standard air.* Unless conditions require otherwise, the ventilating engineer usually assumes a standard air density of 0.075 pound per cubic foot, which is the approximate weight of air at sea level barometric pressure of 29.92″ Hg and 70° F. from 0 to 50 per cent relative humidity.

(*g*) *Air horsepower.* The horsepower output of an air-moving device is known as "air horsepower." It is easily estimated by the formula:

$$\text{A.H.P.} = \frac{(\text{c.f.m.})\ (h)}{6350}$$

where A.H.P. = air horsepower, c.f.m. = cubic feet of air per minute, and h = pressure in inches of water.

Air horsepower is sometimes further qualified as either "total air horsepower" or "static air horsepower." Either of these may be computed from the above equation by using for head (h) the "total pressure" or "static pressure," respectively.

The choice between these two methods of rating must depend on whether the overall fan efficiency is to be expressed as "total efficiency" (also called "mechanical efficiency"), or "static efficiency," inasmuch as fan manufacturers use either or both in their detailed statements of performance.

2. Ejectors, Venturi Ejectors, or Syphon Jets

The venturi ejector is a low-efficiency, air-moving device selected as a last resort when the ventilating system must handle excessive temperatures, corrosive gases, flammable vapors, or viscous or sticky air contaminants that would quickly destroy the effectiveness of axial or centrifugal fans. The air-moving efficiency is highly sensitive to the physical proportions of the outer conduit, and the location of, and air velocity through, the inner jet. Both straight-tube and venturi-type conduits are used, but the latter can be made more efficient. Efficiencies range from 5 to 20 per cent.

Designers who are in a position to compute and specify a high-quality ejector on the basis of the best available aerodynamic data are referred to the comprehensive treatment recently prepared by McElroy.[65] Less precise information has been offered by other writers,[66–68] which is satisfactory for applications where high jet velocities can be produced (8000 to 10,000 l.f.m.) and where one is reconciled to efficiencies in the range of 5 to 10 per cent. The "straight-tube" ejector with a jet diameter one sixth of the straight duct diameter can be used with reasonable success when the connected system has a very low resistance, less than ¼ in. of water.

VI. Design of Ducts for Exhaust Systems

Many special forms and charts have been created and published for the purpose of facilitating the aerodynamic design of ductwork for ventilating systems.[70–78] Unfortunately, some of these devices consume more time than they save, particularly if the designer or estimator is not in constant practice.

[65] G. E. McElroy, *U. S. Bur. Mines Tech. Paper* No. **678** (1945).
[66] F. F. Kravath, *Heating & Ventilating*, **37**, 17 (June, 1940).
[67] F. F. Kravath, *Heating & Ventilating*, **37**, 46 (Aug., 1940).
[68] *Tentative Recommended Good Practice Code and Handbook on the Fundamentals of Design, Construction, Operation and Maintenance of Exhaust Systems.* Am. Foundrymen's Assoc., Chicago, 1938.
[69] A. D. Brandt and R. J. Steffy, *Trans. ASHVE*, **52**, 205 (1946).
[70] J. L. Alden, *Design of Industrial Exhaust Systems.* The Industrial Press, New York, 1939.
[71] J. M. Kane, *Heating & Ventilating*, **42**, 68 (Nov., 1945).
[72] R. D. Madison, *Fan Engineering.* 5th ed., Buffalo Forge Co., 1948.
[73] A. D. Brandt, *Heating & Ventilating*, **42**, 74 (May, 1945).
[74] P. Drinker and T. F. Hatch, *Industrial Dust.* McGraw-Hill, New York, 1936.
[75] W. N. Witheridge, *Air Sanitation and Industrial Ventilation.* Detroit, 1945.
[76] A. Nutting, *Heating, Piping, Air Conditioning*, **9**, 21 (Jan., 1937).
[77] H. R. Phelps, *American Artisan* (Apr., 1943).
[78] (Ductwork) Air Hyg. Foundation Am., *Preventive Eng. Ser. Bull.* No. **2**, Part 5 (1938).

No single form or procedure is offered here as superior to all others, but instead the reader is advised to adopt one that best suits his requirements. If exhaust-system calculations are infrequent, special tabulating and computing forms are less important than a complete list of individual steps for the essential mathematical operations.

A plan of design sequence is now outlined, and this is followed by a brief example of its application.

A. PROCEDURE FOR DESIGN OF EXHAUST SYSTEMS

Lay out the ductwork and design the hoods

1. Prepare a sketch or layout of the exhaust system; use single lines for ducts if simplicity is desired. The layout is more helpful if approximately to scale, although subsequent steps in calculating duct sizes can be carried out even with a very poor drawing.

2. Select the type of hood that will do the best possible job with the smallest amount of air flow. This requires ingenuity in designing enclosures that will not interfere with production, or hoods with movable sections that can and will be operated as planned. There is no point in creating an "ideal" hood that cannot be used without seriously disrupting the production schedule, inasmuch as neither worker nor employer will tolerate its use.

Determine air-flow rates for each exhaust hood

3. Estimate the control or "capture" air velocity required for each operation and type of hood or enclosure. Table 13 suggests control velocities required in the presence of drafts and convection currents. This part of the design process involves a great deal of judgment.

4. Compute the boundary area of the *plane, cylinder,* or *sphere* of influence through which the selected "capture" velocity must operate. The ability to conceive hood arrangements in three dimensions is desirable.

5. Compute the total air flow in c.f.m. for each hood (capture velocity times area of influence) and put this rate on the sketch or diagram of the system for reference purposes.

6. Summarize the air flow for each section of the branch and main ductwork on some form or preferred calculation sheet, or enter the air flows directly upon the diagram or drawing.

Establish air velocities for each duct section

7. Select the minimum effective transport velocity for particulate matter (Table 19). For transporting of gases and vapors, duct velocities can be as low as is consistent with space and weight limitations. Velocities in the range of 1000 to 2000 l.f.m. for gases and vapors are the usual compromise between excessive duct size and unnecessarily high air-horsepower requirements.

8. Figure the nearest practical duct diameter to carry the required c.f.m. at the proper velocity. Consideration should be given to the sheet metal fabricator's standard size increments to avoid unnecessary additional expense. If the available duct sizes are much different from the theoretically required diameters, compute the actual transport velocity for use in subsequent design steps.

Determine the entrance or orifice loss for each hood

9. Compute the velocity pressures corresponding to the air velocities in each branch duct connected to an exhaust opening (see page 336).

10. Estimate the orifice loss for each hood in percentage of velocity pressure in the branch pipe. See Figure 20 and data of Brandt and Steffy.[69]

11. Compute from items 9 and 10 the entrance losses in terms of inches of water.

Determine duct friction and transition losses

12. Compute the losses in elbows, branch to main connections, or other transitions either (*a*) in terms of equivalent straight-pipe diameters (Figs. 21 and 22) or (*b*) in terms of velocity pres-

TABLE 19

Air Velocities for Transporting Various Dusty Materials
(Linear Feet per Minute)

Material	Dust collecting		Pneumatic conveying	
Aluminum dust	4500	6000	..	..
Asbestos	3000	3500	..	..
Ashes, ground	..	..	6000	8500
Bakelite molding powder	2500	3500	..	..
Barley	..	..	5000	6500
Buffing lint	3000	5000	..	..
Cast-iron dust	4000	5000	..	..
Cement, Portland	3500	4000	6000	9000
Clay	3500	4000	..	..
Coal, powdered	3000	4000	4000	5500
Cocoa	3000	3500	..	..
Coffee beans	..	..	3500	5000
Cork, ground	2500	3000	3500	5500
Corn	..	..	5000	7000
Cotton	2500	3000	4000	6000
Cottonseed	..	..	4000	6000
Flour	2500	3500	4000	6000
Foundry dust	3500	5000	..	..
Grain dust	2500	3500	..	..
Granite dust	4000	5000	6000	8000
Grinding dust	3000	5000	..	..
Ground feed (½-in. screen)	..	..	4500	6000
Hemp	..	..	4500	6000
Hog waste	3500	4500	4500	6500
Jute butts	..	..	3500	5000
Jute dust	3000	3500	..	..
Jute lint ("flyings")	2500	3000	..	..
Lead dust	4000	5000	..	..
Leather dust	3000	4000	..	..
Lime	3500	4000	5000	7000
Magnesium dust	4500	6000	..	..
Metal turnings	4000	5000	5000	8000
Oats	..	..	4500	6000
Pulp chips	..	..	4500	7000
Rubber dust	2000	4000	..	..
Rye	..	..	5000	7000
Salt	..	..	5500	7500
Sand or silica	3500	4500	6000	9000
Sawdust, light or dry	2500	3000	4000	6000
Sawdust, heavy or wet	3000	5000	..	..
Soap dust or powder	3000	3500	..	..
Sugar	3000	3500	5000	6000
Tanbark, dry	..	..	4500	7000
Tanbark, damp or leached	..	..	5500	7500
Wheat	..	..	5000	7000
Wood blocks (edgings)	3500	5000	4500	6000
Wood flour (sander dust)	2500	3000	4000	6000
Wool fibers	3000	4500	4500	6000

sures, whichever form corresponds with the data at hand. The equivalent straight-pipe method has the advantage that such transition losses can be added directly to the straight-pipe sections for use with friction charts. The velocity-head method may be preferred by those who are especially familiar with the fundamentals of fluid mechanics.

13. Obtain the duct friction losses from a chart, table, or formula, whichever you prefer to use. Figure 23 is used at this point.

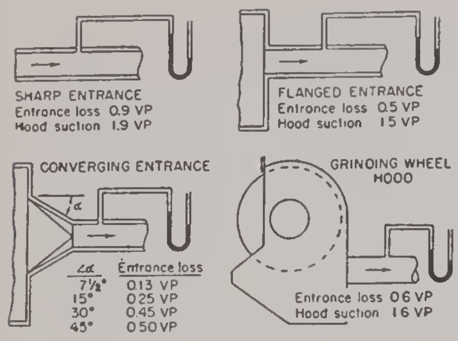


Fig. 20. Exhaust hood entrance losses in relation to velocity pressure (VP) (*courtesy American Air Filter Co.*).

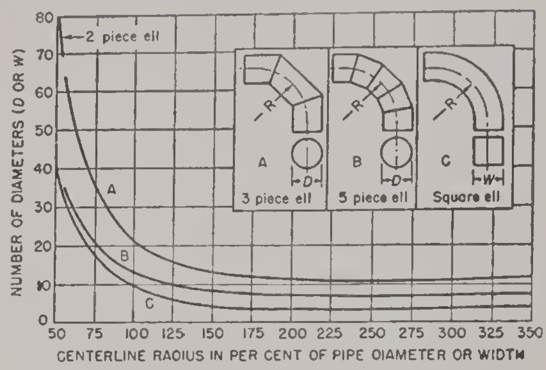


Fig. 21. Pipe-elbow friction losses in terms of pipe diameters.[79]

Balance the pressure drop by adjusting duct sizes

14. Summarize the losses for each branch to determine where to increase or decrease the duct sizes to obtain better balance of pressure drop. (This assumes that balancing will not be left exclusively to manually operated dampers.) The total pressure drop from any point in the system to each upstream opening or exhaust hood should be the same, if balance is to be achieved. This is so because in actual operation, the air-flow quantities through each *open* branch automatically adjust themselves to fulfill this requirement of balance. If the flow through any branch is too high, further closing of a damper increases the friction or energy loss through that branch; this makes it possible for a smaller volume of air flow to create the necessary pressure drop for a condition of balance.

15. If necessary, after the system is balanced on paper to a reasonable degree by adjusting the round duct sizes, conversion to rectangular duct sizes can be made by using Figure 24.

Summarize the system resistance

16. Determine the adjusted total pressure drop of the branch and main duct system by adding the pressure losses beginning with any one exhaust opening and proceeding toward the fan or dust collector. Remember that so long as the branch duct system has been reasonably balanced in accordance with item 14 above, it will be a simple matter to select the safest starting point for totaling the pressure losses. However, if no balancing is attempted, then the losses must be estimated for the single run of duct that you *believe* will have the greatest total resistance. Experienced designers after a few moments of inspection usually can determine the "longest run" in terms of friction loss. In this case the "longest run" implies the course that offers the greatest resistance to air flow, and not necessarily the one longest in terms of feet.

17. Add the resistances of accessory equipment such as air cleaners, weather caps, and shutters. Since this type of equipment varies greatly in resistance to air flow, manufacturers' data should be consulted.

Select an appropriate and adequate fan or air mover

18. From the total air flow in c.f.m. and the total system resistance or S.P. in inches of water, select the type, size, and speed of fan from manufacturers' catalogs that give the highest operating efficiency or lowest H.P. consistent with other considerations, as outlined on pages 325 to 327. Note that the total resistance of the system does not include the velocity pressure at the entrance to the exhaust hoods.

[79] American Society of Heating and Ventilating Engineers *Guide*, 1948.

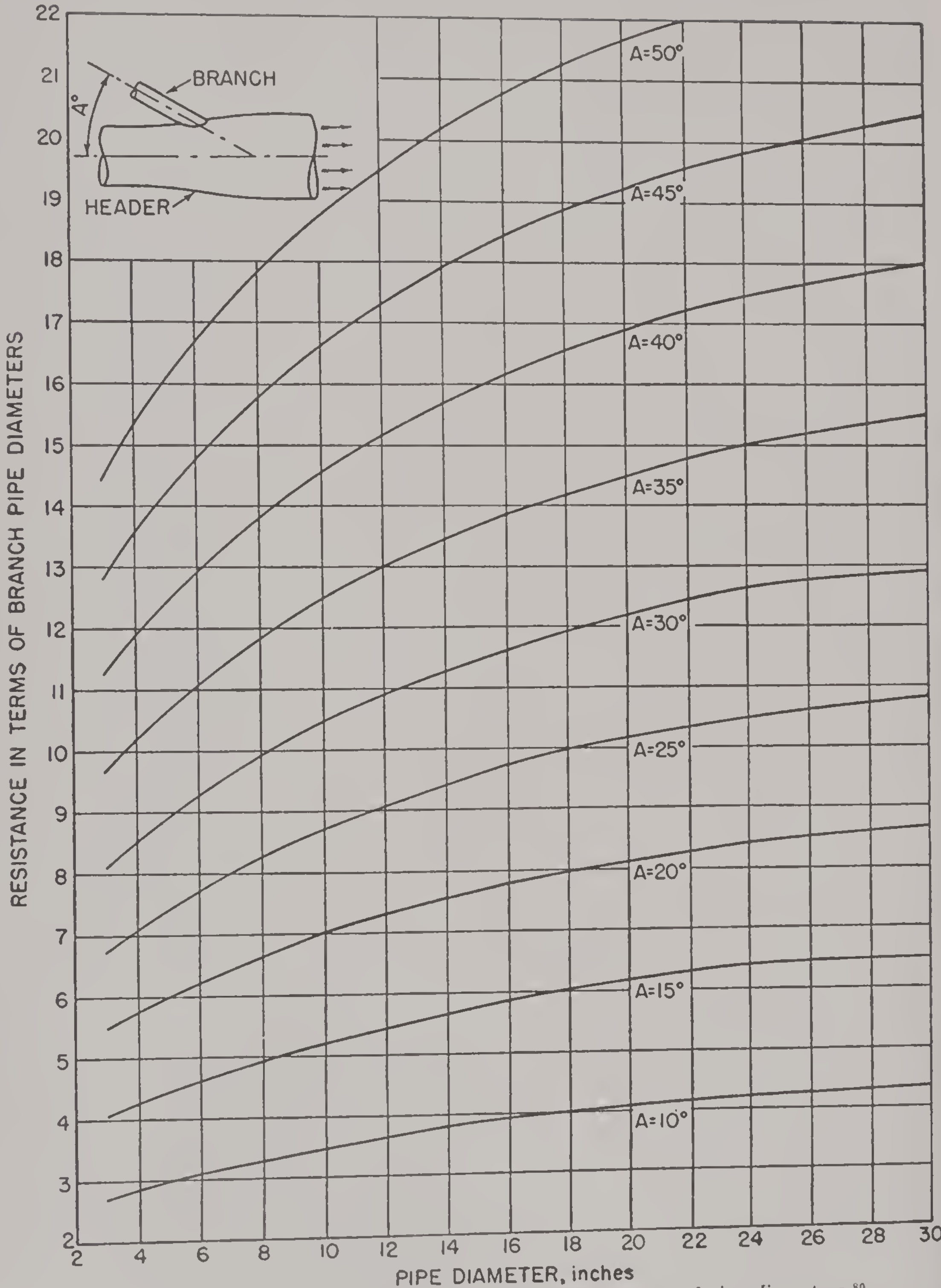


FIG. 22. Branch pipe to main duct transition losses in terms of pipe diameters.[80]

[80] *Tentative Recommended Good Practice Code and Handbook on the Fundamentals of Design, Construction, Operation, and Maintenance of Exhaust Systems.* Am. Foundrymen's Assoc., Chicago, 1938.

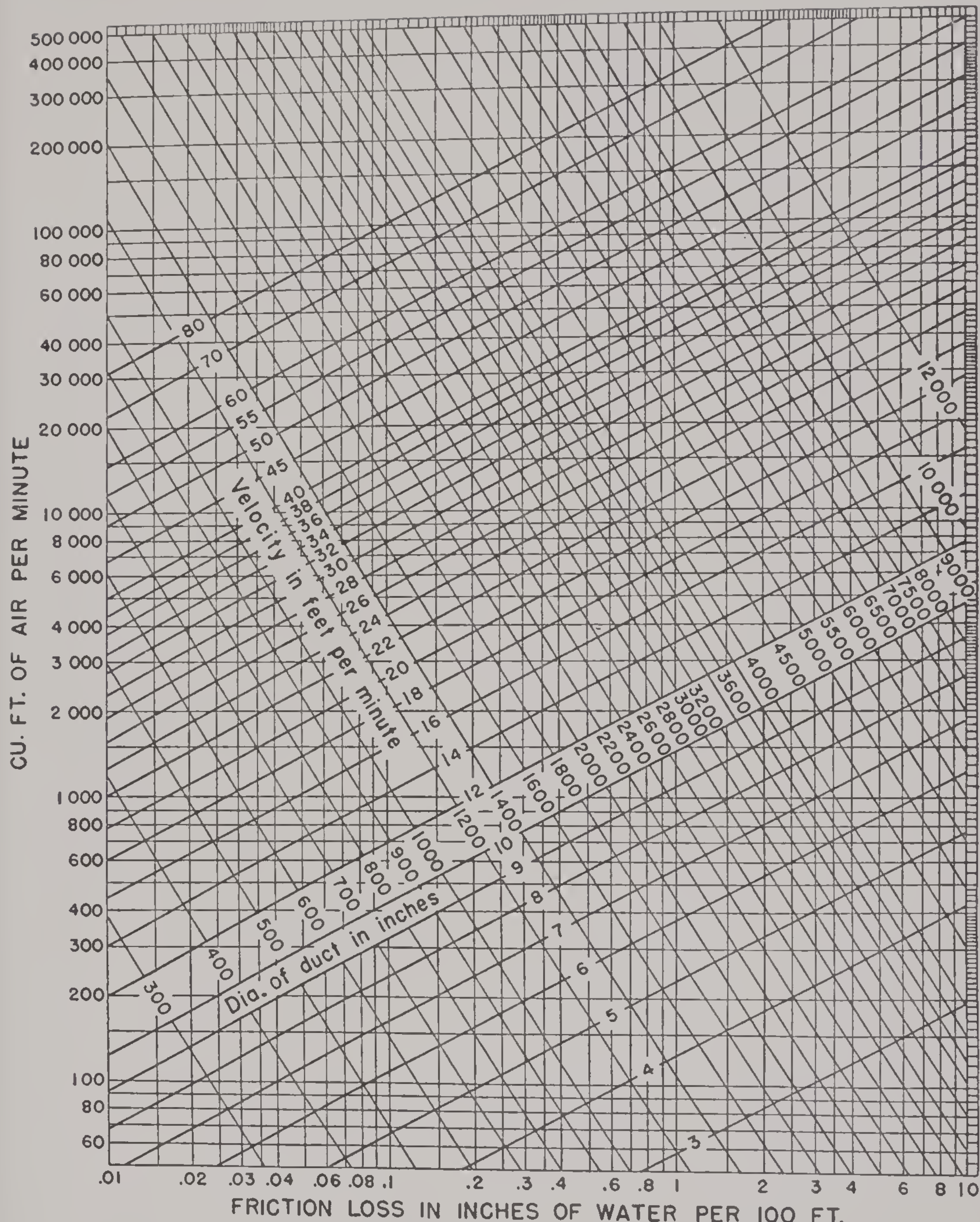


Fig. 23. ASHVE Friction Chart[81] for air flow through round galvanized sheet-metal ducts of average construction with about 40 joints per 100 ft. based on dry air at 29.92 in. barometer and 70° F. (*courtesy ASHVE*).

[81] D. K. Wright, Jr., *ASHVE Journal Section, Heating, Piping, Air Conditioning*, **17**, 577 (Oct.–Nov., 1945).

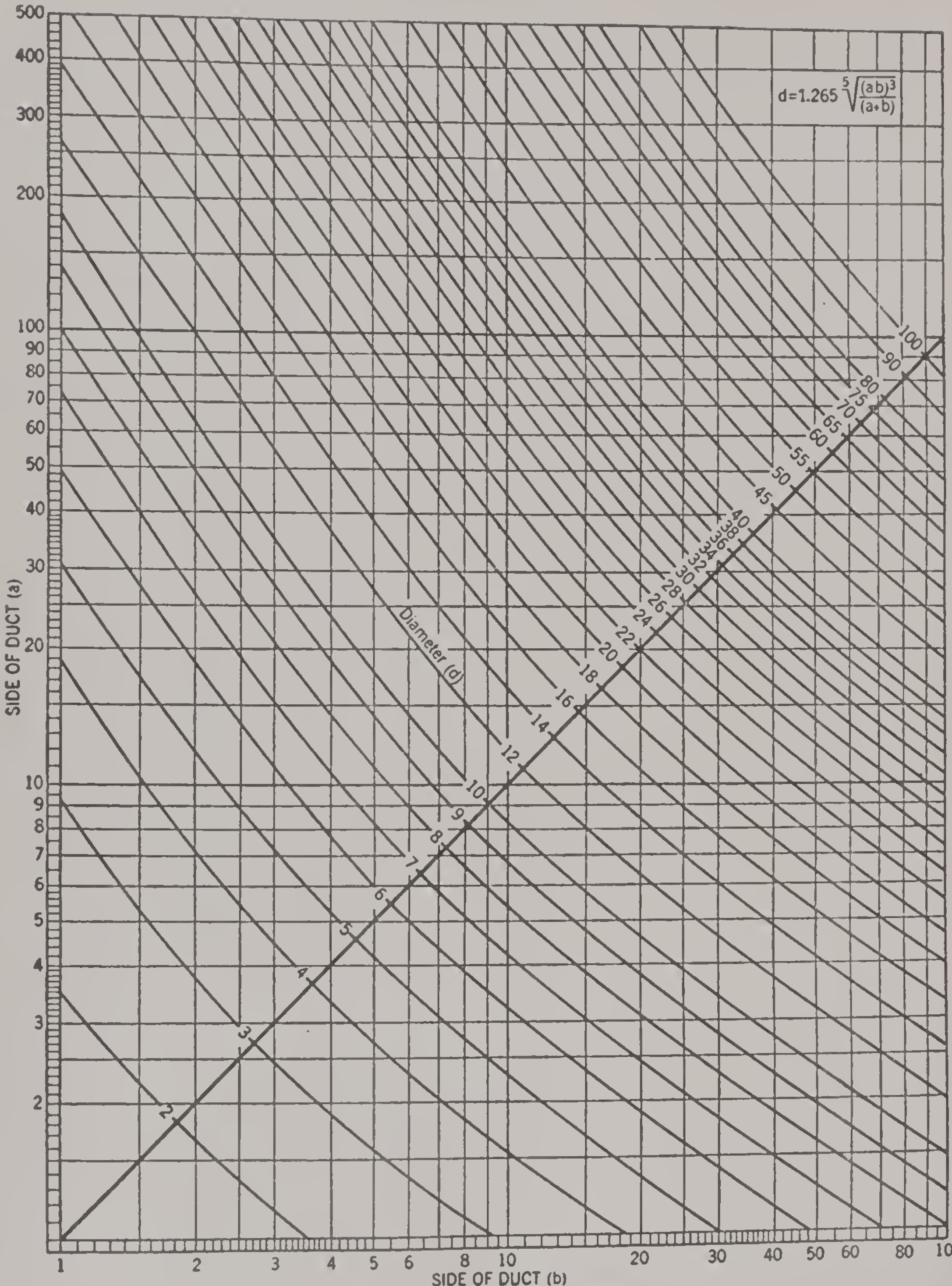


FIG. 24. Chart for converting round to rectangular duct sizes having equivalent friction losses.[82]

[82] American Society of Heating and Ventilating Engineers *Guide*, 1948.

TABLE 20

CALCULATION OF EXHAUST SYSTEM PRESSURE LOSSES								SUMMARY OF LOSSES					
			From friction chart										
Hood and duct section	C.f.m. through duct section	Average design velocity (l.f.m.)	Nearest duct diam. (in.)	Actual duct vel. (l.f.m.)	Friction/100 ft. (in. H_2O)	Total equiv. straight duct (ft.)	Total friction (in. H_2O)	Hood	A	B or C	D	E	Correct E
								V. P.	1.05	0.77	0.86	0.90	1.21
								% loss	50	60	60	50	50
								in. H_2O	0.53	0.46	0.52	0.45	0.61
A – 1	800	4000	6	4100	4.3	15	0.65	—	0.65	—	—	—	
B – 2	300	4000	4	3500	5.1	19	0.97	—	—	0.97	—	—	
C – 3	300	4000	4	3500	5.1	19	0.97	—	—	—	—	—	—
4	1400	4000	8	4000	2.9	20	0.58	—	0.58	0.58	—	—	—
D – 5	600	4000	5.5	3700	4.0	31	1.24	—	—	—	1.24	—	—
6	2000	4000	9.5	4100	2.5	10	0.25	—	0.25	0.25	0.25	—	—
E – 7	1000	4000	7	3800	3.0	34	1.02	—	—	—	—	1.02	1.49
8	3000	4000	12	3800	1.6	15	0.24	—	0.24	0.24	0.24	0.24	0.24
SUBTOTAL FOR BALANCING PURPOSES:									*2.25*	*2.50*	*2.25*	*1.71*	*2.34*
										2.00 *dust collector*			
9	3000	3000	14	2800	0.75	19	0.14	—	—	0.14	—	—	—
10	3000	2000	16	2200	0.39	30	0.12	—	—	0.12	—	—	—
Correct										0.10 *weather cup*			
E – 7	1000	—	6.5	4400	4.5	33	1.49	—	—	—	—	—	—

TOTAL RESISTANCE OF SYSTEM: *4.86*

B. DESIGN EXAMPLE

Figure 25 is a line diagram of a simple grinding exhaust system that has been aerodynamically designed according to the plan outlined above. The results are summarized in Table 20.

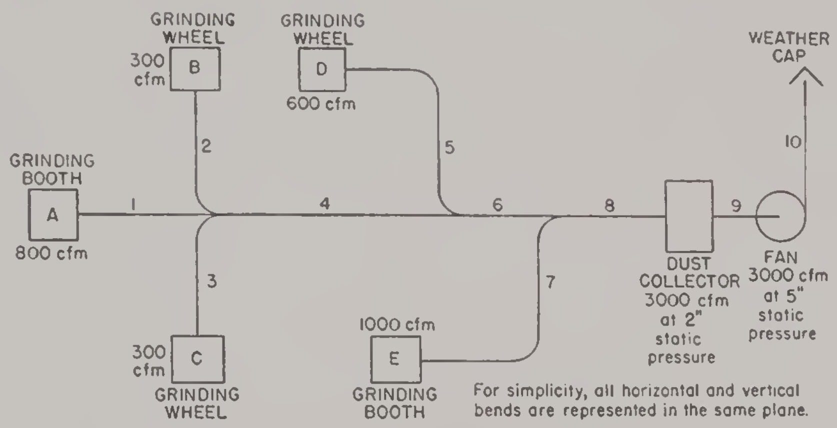


FIG. 25. Line diagram of an exhaust system.

C. RELATION BETWEEN AIR VELOCITY AND VELOCITY PRESSURE

The dynamic or kinetic energy of moving air may be expressed in terms of the equivalent static or potential energy of a vertical column of water. Thus, the downward pressure exerted by a column of water 1 in. high is enough to balance the pressure created by an air stream that impinges against a stationary surface with a velocity of approximately 4000 l.f.m. We say, therefore, that 4000 l.f.m. has a "velocity head" or "velocity pressure" of 1 in. of water. Conversely, if air under a pressure of 1 in. of water is allowed to escape to the atmosphere through a frictionless orifice, it will emerge with a velocity of 4000 l.f.m.

For most applications in the field, the following approximate formula can be used in either of the two forms given:

$$\text{air velocity, or} \quad V = 4000\sqrt{\text{V.P.}}$$

$$\text{velocity pressure, or} \quad \text{V.P.} = (V/4000)^2$$

D. THE WRIGHT FRICTION CHART

At the request of the ASHVE Committee on Research, Wright[53] analyzed most of the air-duct friction charts in use in 1945 for the purpose of determining which chart, if any, should be sponsored by the Society. He concluded that none of the existing friction charts could be considered as representing the best information in fluid mechanics, and accordingly designed a new chart, which is represented here as Figure 23. This chart applies to the flow of dry air at 70° F. and 29.92 in. Hg barometer through round straight galvanized sheet-metal ducts of average construction with about 40 slip joints per 100 ft.

[53] D. K. Wright, Jr., *Heating, Piping, Air Conditioning*, 17, 577 (Oct.–Nov., 1945).

Friction losses in pipes or ducts that differ considerably from the conventional sheet-metal construction can be computed from the following formula in combination with Tables 21 and 22:

$$\frac{\text{inches of water}}{\text{hundred feet}} = f\left(\frac{1200}{\text{diameter in inches}}\right)\left(\frac{\text{l.f.m.}}{4000}\right)^2$$

The procedure is to: (*1*) select an appropriate roughness measure (ϵ) from Table 21; (*2*) compute relative roughness, ϵ/D, in which D is pipe diameter in feet; (*3*) compute Reynolds Number from formula on page 338; (*4*) use Reynolds Number and relative roughness in Table 22 to find the friction factor, f; (*5*) use f in the equation above to find the air-flow friction loss in inches of water per hundred feet of pipe.

TABLE 21

Roughness Measure (ε) for Various Kinds of Pipe[84]

Kind and condition of pipe	ϵ, ft.
Perfectly smooth drawn tubing	0.000005
Commercial steel or wrought iron, new	0.00015
Asphalted cast iron	0.0004
Galvanized iron (used for Fig. 23)	0.0005
Cast iron	0.00085
Wood stave	0.0006 to 0.003
Concrete	0.001 to 0.01
Riveted steel	0.003 to 0.03

TABLE 22

Friction Factors Based on Reynolds Number and Pipe Roughness[84] *for Use with Friction Formula on Page 336*

Relative roughness,[a] ϵ/D	Reynolds Number			
	10^4 10,000	10^5 100,000	10^6 1,000,000	10^7 10,000,000
0.00001	0.030	0.018	0.012	0.009
0.0001	0.031	0.0185	0.0135	0.012
0.0005	0.032	0.0205	0.0175	0.017
0.001	0.032	0.022	0.020	0.0195
0.005	0.038	0.031	0.030	0.030
0.01	0.043	0.038	0.038	0.038
0.03	0.060	0.057	0.057	0.057
0.05	0.074	0.072	0.072	0.072

[a] ε = roughness measure of pipe surface in feet and D = inside diameter of pipe in feet.

For kinds of pipe not listed in Table 21 the roughness measure can be selected for the material most likely to be similar in surface characteristics. In estimating the internal pipe roughness, consideration should be given to surface treatment of the pipe for corrosion resistance, and the possibility of surface modification by the

[84] L. F. Moody, *Trans. Am. Soc. Mech. Engrs.*, **66**, 671 (1944).

accumulation of particulate matter, especially if hygroscopic or unusually electrostatic.

E. REYNOLDS NUMBER

The Reynolds Number used in fluid mechanics and required in the use of Table 22 is a "dimensionless" figure that may be computed from the following equation:

$$\text{Reynolds Number} = \frac{\text{(velocity in f.p.s.) (diam. in ft.)}}{\text{(kinematic viscosity in sq. ft./sec.)}}$$

A convenient, approximate form that applies to most air-flow conditions in ventilating systems, and is adjusted to the conventional units, is the following:

$$\text{Reynolds Number} = 8.5 \text{ (l. f. m.) (diam. in in.)}$$

The constant 8.5 in this equation is based on a kinematic viscosity for air at 70° F. and 29.92″ Hg barometer of 0.000163 sq. ft. per second. For values of kinematic viscosity at high and low temperatures and high pressures, see the convenient chart presented by L. G. Miller.[85]

F. FLEXIBLE METAL, CANVAS, OR RUBBER DUCTS

The friction of air flow through flexible ducts is considerably higher than for straight sheet-metal pipes. If the inside surface is deeply corrugated, the friction loss may be two to four times the loss for smooth pipe of equal diameter. Furthermore, it is necessary to anticipate increased friction loss to a degree depending upon the amount of curvature to which the duct can or will be subjected.

Not all flexible ducts should be treated as unusually high-resistance material. Some natural or synthetic rubber ducts are so constructed that the inside is relatively smooth, while the corrugations due to metal reinforcement appear on the outside surface. Also, some metal flexible ducts are so rigidly constructed that sharp curvature is impossible. Field tests of friction loss should be made if its effect on air flow or power consumption is of serious consequence.

G. ADJUSTABLE DAMPERS OR FLOW REGULATORS

The tendency still exists to install in each branch of an exhaust or ventilating system some type of damper to make possible an initial or periodic variation in the amount or distribution of air flow. This practice has reached the ultimate in disfavor in connection with the handling of highly explosive dusts that may collect or settle out in the vicinity of dampers as a result of eddies or sudden changes of flow direction. A great many objections to dampers have been expressed among designers of exhaust systems, but the fact remains that in many cases their use has made possible the correction of air-flow distribution when the original design did not succeed in anticipating the best proportion of ventilation for each machine or process in the system. It is true that tremendous power has been wasted throughout the years by the work of dragging air through the constrictions imposed by dampers, and efforts to improve the accuracy of ventilation estimates and designs must be

[85] L. G. Miller, *Trans. ASHVE*, **43**, 71 (1937).

encouraged. Likewise, some attention must be given to the design of better flow-regulating devices to give the user the flexibility his operations may demand. Designs also can be, and have been, made to permit adjustments that cannot be disturbed by unauthorized persons without obvious damage or destruction.[86]

H. PNEUMATIC CONVEYING SYSTEMS

Light bulky materials, such as wood shavings, textile fibers, paper trimmings, ground cork, and grain products, can be transported by air without excessive power requirements and without damage to the materials or conveying equipment. Conveying velocities may be of the same order as for dust-handling systems, or they may be much higher, as indicated in Table 19, with resultant increase in the power requirement. The quantities of air required for pneumatic conveying vary approximately from 100 cu. ft. per pound of light fluffy material such as "open cotton" at 3000 l.f.m. to about 25 cu. ft. per pound of heavy solid materials at 8000 l.f.m.

I. CONSTRUCTION SPECIFICATIONS FOR VENTILATING SYSTEMS

The designer must obtain the codes and standards that apply to his industry, state, or trade association to be certain that his preferences do not conflict with locally established or legalized practice. It is not possible here to formulate a list of specifications that will have nation-wide acceptance without removing most of the details that would be of interest. Furthermore, construction materials, methods, and standards are improving yearly.

The *Annual Guide* of the American Society of Heating and Ventilating Engineers is suggested as a source of information on construction features that will be kept reasonably up-to-date by the frequent revisions prepared by authorities among the society's membership. Among state codes, the most widely publicized in the field of industrial ventilation at the present time are those prepared by the Division of Industrial Hygiene of the New York State Department of Labor and they might be used as a guide in states having no detailed codes in effect. Among nonofficial codes, the American Standards Association's list of approved and adopted codes on ventilation is already substantial and will grow continuously. It will become an increasingly important source of technical and design information as professional organizations assemble their material for submission to the ASA.

J. CENTRAL VS. UNIT EXHAUST SYSTEMS

In many industrial plants, the operating personnel are driven to seek the most flexible equipment for the constant shuffling and reshuffling of plant layout and operational sequence. Process ventilation is no exception. We are evidently in the stage of a transition from elaborate interconnected centralized duct systems to the individual unit exhaust and air-cleaning devices for single or small groups of industrial machines.

The premium price paid for a large collection of individual exhaust ventilating units is the price of flexibility. This transition is somewhat parallel to the evolution

[86] B. S. Malin, *Heating & Ventilating*, **42**, 75 (Feb., 1945).

from overhead lineshaft drives in nineteenth century plants to the individual motor drives for the machinery of contemporary mass production. There are still some factories that have not converted their machine shops from flat-belt drives off overhead lineshafts to individual electric motor power for each machine. In such shops the rearrangement of machinery is a minor problem, and the need for self-contained units may not be great enough to justify the cost of converting the method of power transmission. Likewise, there are many exhaust ventilating jobs that do not need to contend with the continuous relocation of processes, and the use of a centralized duct system with a single fan, motor, and air cleaner remains the best and most economical arrangement, both from the standpoint of installation costs and perpetual maintenance expenses.

K. MAINTENANCE OF VENTILATING EQUIPMENT

Too frequently the designer has no further control over the ventilating system after it is placed in use. Whether he made provisions for alterations and additions, or issued instructions that no change must be made without a review of the design, the fact remains that sooner or later something will be done to upset the original plan, and place new burdens upon the fan, collector, and ductwork for which they were never prepared. Accordingly, the alert redesigner or investigator will proceed with caution when appraising the original design.

Innumerable failures in mechanical ventilation are due to inadequate care or maintenance, and this applies to nearly every part of the system, whether movable or stationary. When it is realized that contaminated air is in constant motion through the hoods, ducts, cleaners, and fan, it is readily appreciated that the entire air-handling equipment should be classified as dynamic rather than static. Transparent ducts would settle this point beyond doubt in many cases.

Perhaps the best assurance that mechanical ventilation is functioning properly is a scheme of periodic inspection and testing. The following, and concluding, section in this chapter outlines the practical methods of observing and measuring air flow, and successful maintenance departments have learned to use these or similar methods to demonstrate and facilitate first-class performance.

VII. Air Flow Observation and Measurement

Air movement is observed or measured by the ventilating engineer in four locations: (*1*) in open or free air spaces, indoors or outdoors; (*2*) at the face of an exhaust or suction opening; (*3*) at the face of a supply or pressure opening; and (*4*) inside ducts, pipes, or conduits.

The kinds of instruments or procedures in use for determining the velocity and direction of air motion may be classified as: (*1*) visual, (*2*) mechanical or pneumatic, (*3*) chemical, and (*4*) thermal or electrothermal.

"Each instrument has its special advantages, the rotating-vane anemometer being the best averaging instrument, and the bridled-vane anemometer (Velometer) the most convenient to use for *spot readings*. The heated thermometer has the

widest velocity range, the heated thermocouple is best adapted for distant reading, and the kata thermometer is the least expensive."[87] The Pitot tube is still widely used in fan testing, exhaust system inspection, and aerodynamic research, but the industrial hygiene engineer has found an increasing need for his services in the 50 to 500 l.f.m. range of air velocities, for which the standard Pitot tube is not practical.

A. VISUAL METHODS OF OBSERVING AND MEASURING AIR FLOW

The engineer is inclined to pass over the simple visual methods of observing air-flow rates, directions, and dispersions as not possessing the requisite accuracy and refinement. The fact is that some of the best mechanical instruments now in use for the measurement of air flow have become popular because they have incorporated the principle of rapid and convincing visual indication. Field measurements in industrial ventilation do not demand the accuracy required in a fan-testing laboratory, and accordingly they offer attractive opportunity for the compromise of accuracy, convenience, speed, and portability.

1. Smoke Clouds

Low velocity air flows below 150 l.f.m. have been observed and measured in mine ventilation by smoke clouds generated by a device developed by the United States Bureau of Mines,[88, 89] and which is now commercially available (Ventilation Smoke Tube, *Mine Safety Appliances Co.*, Pittsburgh, Penna.) for any low-velocity observations in general or local industrial ventilation. In mine applications, the progress of one or more separate clouds may be timed with a stop watch, which is feasible of course only at low air velocities. High air velocities diffuse the smoke too quickly unless the observations are made outdoors on the progress of very large masses of air using dense clouds of smoke.

The "smoke" or fume can be generated by passing air over fuming sulfuric acid, tin tetrachloride, titanium tetrachloride, or other fuming agent that will yield a dense cloud of light color. For convenience, the active agent can be impregnated onto pumice granules or other adsorbent material and sealed into a glass ampoule. In use, the sealed tips are broken off the ampoules and an aspirating bulb is attached for forcing air over the granules. The fuming materials generally used are corrosive and must be handled with care.

Smoke observations in the vicinity of exhaust or supply openings can be very helpful supplements to measurements made with anemometers.[90] They are likewise used successfully in studying the aerodynamic behavior of fans and vehicles, and in wind-tunnel research. High-speed photography has overcome the human difficulty of tracing smoke currents in rapid air streams.

[87] G. L. Tuve, D. K. Wright, Jr., and L. J. Seigel, *Trans. ASHVE*, **45**, 645 (1939).
[88] S. H. Katz and J. J. Bloomfield, *U.S. Bur. Mines Repts. Investigations* No. **2505** (1923).
[89] J. J. Bloomfield and J. M. DallaValle (Determination, Control, Industrial Dust). *U.S. Pub. Health Service Bull.* No. **217** (1935).
[90] T. Lewis, *Trans. ASHVE*, **32**, 279 (1926).

2. Floating Objects

Floats, balloons, flags, ribbon streamers, or similar light objects have been used as long as the flow of air has been of interest to man. The familiar observation of flags or banners sustained by the wind no doubt accounts for the very convincing nature of ribbon streamers attached to ventilating grilles. Many building superintendents have resorted to this method of demonstrating to the public that the ventilating system really was in operation, notwithstanding the lack of perceptible air movement in the occupied zone. An "indicating-ribbon" grid has been used as a research tool together with a Velometer for observing and measuring the movement of free air streams.[91]

A visual approach that has acquired an unwholesome reputation is the tossing of small objects toward the inlets or exhaust openings of mechanical ventilating systems to test their suction ability. The maintenance department finds a great variety of discarded paper, cloth, leather, wood, and even heavier objects scattered throughout exhaust systems, and occasionally traces the damage or failure of ventilation to such obstructions. The "exhaust-hood reflex" on the part of passers-by is evidently similar to the "wet-paint reflex," and it has caused some plants to install rugged screens at each opening in defense of the exhaust fan and air-cleaning equipment.

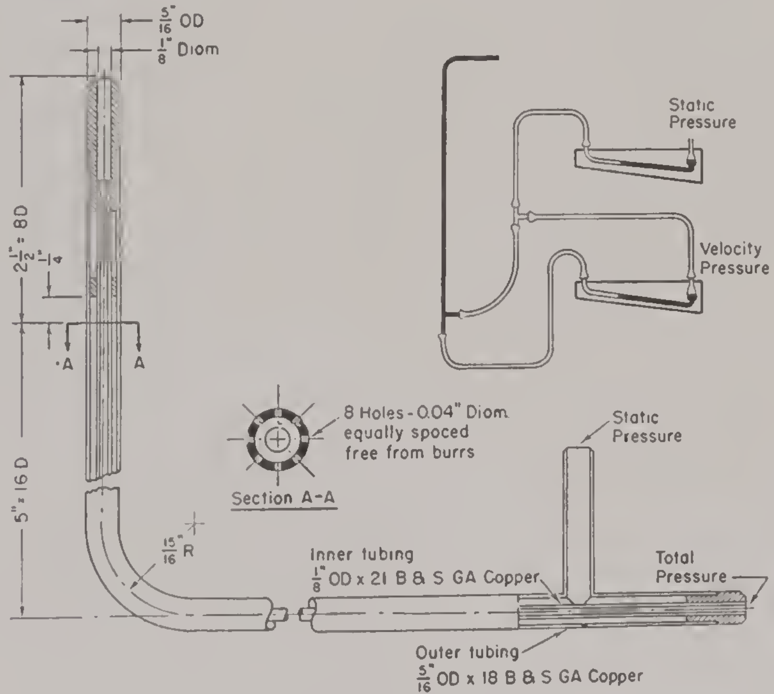


Fig. 26. Standard Pitot-static tube.[92]

[91] G. L. Tuve, D. K. Wright, Jr., and L. J. Seigel, *Trans. ASHVE*, **45**, 645 (1939).
[92] American Society of Heating and Ventilating Engineers *Guide*, 1948.

B. STATIC AND DYNAMIC PRESSURE INDICATORS

1. The Pitot Tube or Pitot-Static Tube

The primary air velocity meter against which all other instruments or metering devices are calibrated is the Pitot tube, named after the French scientist Pitot. His original tube was simply a total-head or impact tube, and its measurements, of course, included both static and velocity components. The Pitot tube as now used is actually a Pitot-static tube combination that permits the direct reading of velocity pressure (Fig. 26).

The Pitot tube must be used with some type of air-pressure indicator, generally a vertical or inclined manometer. Duct velocities are determined either as centerline readings with the Pitot tube corrected to average velocity, or as "traverses" across the duct section according to a definite schedule of point locations that will assure average velocity determinations.[93]

Very sensitive *micromanometers* are available for measuring pressure differentials as low as 0.0001 in. of water[94] but these instruments obviously are limited to laboratory applications. For small ducts it may be necessary to construct a special Pitot tube, geometrically similar to the Standard shown in Figure 26. A double-ended tube, one end pointed downstream, and one upstream, has been designed for low velocity measurements.[95]

2. Suction at Exhaust Hood Throat

The "negative" pressure existing at the throat of an air exhaust opening or hood can be used to estimate the quantity of air that will enter the hood. Static suction at the throat of hoods has been specified in numerous codes and standards on the assumption that it bears a constant relationship to the ventilation rate. Discovery of the fact that many variables can operate to invalidate the suction test has resulted in a widespread distrust of the suction method of estimating air-flow rates.

Properly used, the static-suction method is convenient and reliable. It requires, however, a sound knowledge of hood characteristics and the amount of energy that may be lost in the passage of air from the atmosphere into the exhaust opening. The mathematics of hood entrance losses or entry coefficients are not clearly understood by the nontechnical inspector of industrial process ventilation, and for this reason the relation between hood suction and air-flow rate generally must be determined by engineers familiar with exhaust-hood computations. An equally satisfactory procedure is the calibration of a system by simultaneous tests with a suction device and an air-velocity indicator such as the Velometer or Pitot tube. Subsequent routine tests of suction by nontechnical personnel can then be translated into their corresponding rates of air flow for the system under observation.

[93] *NAFM and ASHVE Standard Test Code for Centrifugal and Axial Fans.* 3rd ed. National Association of Fan Manufacturers, 1938.

[94] "The Wahlen Gage (Illinois Micromanometer)," *Univ. Illinois Eng. Experiment Station Bull.* No. **120** (March, 1921).

[95] F. R. Ingram, E. Diez-Canseco, and L. Silverman, *Heating, Piping, Air Conditioning,* **14**, 702 (Nov., 1942).

Details of this method have been described,[96, 96a] and recent data on exhaust-hood entrance losses have been reported by Brandt and Steffy.[97]

3. Venturi and Orifice Meters. Nozzles

These are devices placed in a pipe to measure the rate of fluid flow. They accelerate the flow of fluid for the sole purpose of causing a temporary and measurable conversion of static pressure into velocity pressure. As the fluid passes through the orifice or venturi constriction, its velocity increases, and likewise its *velocity pressure increases* (see page 336). The static pressure, therefore, must *decrease correspondingly* to satisfy the conditions of the following common equation:

$$\text{total pressure} = \text{static pressure} + \text{velocity pressure}$$

This temporary drop in static pressure is observed by installing a "U" tube or manometer across the orifice, venturi, or nozzle with the upstream "tap" about one pipe diameter ahead of the point of constriction, and the downstream tap opposite the "vena contracta" or point of highest velocity.[98–101]

The static pressure drop is equal to the rise in velocity pressure (neglecting losses) and therefore is an index of the velocity pressure increase. With appropriate formulas or calibration data that take account of friction losses, the pressure differential on the manometer indicates the rate of air flow through the orifice, venturi, or nozzle.

A well-constructed venturi or nozzle does this job efficiently and permits almost complete recovery of the initial static pressure. The thin-plate orifice, on the other hand, is quite inefficient, and may cause a 30 per cent loss of static pressure before the air settles down to its original pipe velocity.

The air flow measured by an orifice, venturi, or nozzle is computed from the following formula:

$$\text{c.f.m.} = 4000\, CfA\sqrt{h}$$

where 4000 = approximate constant representing $1098/\sqrt{d}$ (where d is air density in pound per cubic foot), C = "coefficient of discharge," f = "velocity of approach factor" = $\sqrt{1/(1 - r^4)}$ (where r is the ratio of orifice, venturi, or nozzle throat diameter to main pipe diameter), A = area of orifice, nozzle, or venturi throat in square feet, and h = observed static pressure differential in inches of water.

Discharge coefficients commonly combine the constants C and f, and therefore care should be taken to note which form of coefficient is used, if f is not close to 1.0.

[96] W. C. L. Hemeon, Ind. Hyg. Foundation, Pittsburgh, *Preventive Eng. Ser. Bull.* No. 3, Part 2 (1946).

[96a] J. M. DallaValle, *Heating & Ventilating*, **43**, 70 (1946).

[97] A. D. Brandt and R. J. Steffy, *Trans. ASHVE*, **52**, 205 (1946).

[98] E. Ower, *The Measurement of Air Flow.* 2nd ed., Chapman & Hall, London, 1933.

[99] Fluid Meters—Their Theory and Application. *Am. Soc. of Mech. Eng. Special Research Committee on Fluid Meters* (1931, 1933, 1937).

[100] Flow Measurement by Nozzles and Orifice Plates. *Am. Soc. of Mech. Eng. Power Test Codes*, 1940, Chap. 4 of Part 5.

[101] S. A. Moss, *Trans. Am. Soc. Mech. Engrs.*, **49–50**, APM-3 (1927–28).

The venturi meter has a high discharge coefficient, 0.96 to 0.98, so long as the upstream and downstream transitions are correctly proportioned and smoothly constructed. The thin-plate, square-edged orifice has a coefficient in the range of 0.60 to 0.65, with the exact value depending upon the location of the differential pressure connections, the ratio of orifice to pipe diameter, and the sharpness of the orifice edge.[98–101] The rounded approach orifice or "nozzle" when properly made has a coefficient approaching or exceeding 0.99.[102, 103]

4. Propeller or Revolving-Vane Anemometer

This is the familiar device that for many years was simply known as the *anemometer* to the heating and ventilating engineer. And it is still in common use, especially for the measurement of air flow through grilles and registers for space ventilation.[104–107] It consists of a small windmill geared to a revolution counter that is calibrated to indicate directly the number of feet of air that has passed through the vanes over a period of time measured with a stop watch. This type of meter is best suited to air velocities above 200 l.f.m., although very accurate calibration of the larger-diameter vane anemometers can reduce the errors that are caused by friction of the mechanism and inertia of the rotor.

5. Deflecting-Vane Anemometer

This instrument, commonly known as the Velometer (trade name of the Illinois Testing Laboratory, Chicago) consists of a pivoted vane enclosed in a case, and so mounted with a pointer that the pressure exerted by air passing through the instrument is read directly on a scale calibrated in l.f.m. This direct-reading feature makes it admirably suited to spot and exploratory testing of air movement in a minimum of time. A large variety of attachments is available for measuring duct velocities, static pressures, and air flow from grilles and into exhaust hoods. The special jets or attachments must be calibrated together with the instrument. An air filter is provided to protect the interior mechanism against dust when the instrument is used in contaminated atmospheres.

Calibration should be checked at regular intervals depending upon the amount of use or the possibility of corrosion or accumulation of dirt. Initially the instrument, as currently constructed, is adjusted to give readings with a maximum error of ± 3 per cent of the *full scale reading*. This means that the lower-velocity end of any scale on the instrument contains a proportional error greater than occurs at the high-velocity end of the scale. Consequently, if several scales are available, it is best to

[102] H. S. Bean, E. Buckingham, and P. S. Murphy, (Square Edged Orifices), *J. Research Natl. Bur. Standards*, **2**, 561 (1929).

[103] J. F. Downie Smith, (Rounded-Approach Orifices), *Trans. Am. Soc. Mech. Engrs.*, **56**, 791 (1934).

[104] L. E. Davies, *Trans. ASHVE*, **36**, 201 (1930); **37**, 619 (1931); **39**, 373 (1933).

[105] ASHVE *Guide*, 1948.

[106] G. L. Tuve and D. K. Wright, Jr., *Trans. ASHVE*, **46**, 313 (1940).

[107] G. L. Tuve, *Heating, Piping, Air Conditioning*, **13**, 740 (Dec., 1941).

select the one that permits air velocity readings to be made at the upper half of the scale.

C. CHEMICAL METHODS OF MEASURING VENTILATION

Earlier in this chapter mention was made of the use of carbon dioxide concentrations in occupied rooms to determine the efficiency of ventilation. Yaglou, Riley, and Coggins[108] showed that such tests were unreliable unless the ventilation rate was low enough to allow each unit of incoming air to remain in the room for a sufficient time to become thoroughly mixed with contaminated air, and thereafter leave the room carrying its full share of carbon dioxide.

With the above limitation in mind, it is possible to determine dilution-ventilation efficiency by carbon-dioxide measurement when all other variables are known or controlled during gas sampling. If the dilution efficiency of a given system of air distribution operating at varying rates of air flow has been predetermined by calibration measurements, subsequent routine measurements can be reliable, and the air distribution characteristics may be safely compared with those of other rooms or with the characteristics of other types of supply and exhaust arrangement.

Hatch and Walpole[109] offer an interesting method of studying the ventilation requirements for some types of industrial processes, especially where the principal factor controlling the required air flow is the air displaced by the process. Their procedure consists in feeding a test gas, such as carbon dioxide, into the exhaust air stream at a known rate and measuring its concentration at the desired point downstream from the feed point. The degree of dilution establishes the rate of air flow.

D. THERMAL AND ELECTROTHERMAL MEASUREMENTS OF AIR FLOW

Thermal instruments are preferred for the measurement of low air velocities so long as the instrument does not generate its own convection currents in disturbing quantity. Hot-wire anemometry has been used many years in specialized industrial control systems and in laboratory research. This and other thermometric devices are reviewed briefly in this section.

1. *Kata Thermometer* (*Standard and Electric*)

The kata thermometer has been calibrated as an air-velocity instrument, although its original purpose was estimation of the cooling effect of an environment upon human beings.[110–112] It is perhaps the least expensive of the instruments that can be used for air-velocity determinations, but its fragility and need for auxiliary equipment (stop watch and heat source) have kept it from becoming a popular

[108] P. Yaglou, E. C. Riley, and D. I. Coggins, *Trans. ASHVE*, **42**, 133 (1936).

[109] T. Hatch and R. H. Walpole, Jr., Air Flow Measurement by the Dilution Method. Ind. Hyg. Foundation, Pittsburgh, *Preventive Eng. Ser. Bull.* No. **3**, Part 1 (1942).

[110] C. P. Yaglou and K. Dokoff (calibration of the kata thermometer), *J. Ind. Hyg.*, **11**, 278 (Oct., 1929).

[111] M. B. Jacobs, *Analytical Chemistry of Industrial Poisons, Hazards, and Solvents.* Interscience, New York, 1941.

[112] C. P. McCord and W. N. Witheridge, *J. Am. Med. Assoc.*, **111**, 1647 (1938).

device for industrial use. It is available in two ranges, the red or "low-temperature" cooling from 100 to 95° F., and the blue or "high-temperature" cooling from 130 to 125° F.

Hill developed an *electric kata thermometer* with a "cooling-power" scale etched on the stem instead of temperature in degrees. A fixed amount of heat was supplied by means of an electric heating coil built into the bulb of the instrument.[113]

2. Electrically Heated Thermometer Anemometer

This instrument, designed by Yaglou,[114] is a mercurial glass thermometer with an electrical resistance winding around the bulb. Electric current of a measured quantity is supplied to raise the temperature of the thermometer bulb. The rate of air movement across the bulb is directly related to its cooling effect as indicated by the temperature reading. The difference in temperature between a heated and an unheated thermometer, together with a reading of current or voltage applied, can be translated by a calibration formula or curve to the air velocity in l.f.m. By varying the voltage across the winding, the velocity range can be selected at will between 10 and 6000 l.f.m. for the standard instrument.

3. Electrically Heated Wire Anemometer

Another instrument suitable for the measurement of low air velocities in open areas, as well as in very close quarters, is the "hot-wire" anemometer. In this case the speed of air flow across the wire is indicated by the temperature-resistance relationship. It can be adapted to remote reading and recording, and a group of instruments may be connected together to give the average velocity in a space. By suitable switching arrangements, air velocities at individual points within a test space can be read or recorded. A portable model has been designed[115] which proved to be convenient in mine-ventilation surveys.

4. Electrically Heated Thermocouple Anemometer

This instrument is used when it is desirable to measure air flows with a number of separate instruments and a single potentiometer. It is especially advantageous where low velocities are to be measured in a closed space without disturbance caused by an observer.[116] It can be made practically free from directional effects and, by properly adjusting the heating currents, it is possible to measure air velocities with satisfactory precision over a wide range, without excessive temperature differences between the air and the heated thermocouple. Air velocity is expressed in terms of the electromotive-force difference between heated and unheated thermocouple junctions.

[113] L. Hill and D. Hargood-Ash, *J. Physiol.*, **54**, 45 (1920–21).
[114] C. P. Yaglou, *J. Ind. Hyg. Toxicol.*, **20**, 497 (Oct., 1938).
[115] D. D. Wile, *Trans. ASHVE*, **42**, 349 (1936).
[116] A. P. Kratz, A. E. Hershey, and R. B. Engdahl, *Trans. ASHVE*, **46**, 351 (1940).

E. AIR MOVEMENT IN UNCONFINED SPACES

Tuve, Wright, and Seigel[117] make the following suggestions for measuring air velocities in open rooms:

"1. Where directional effects are important, use a mechanical-type instrument.

"2. Where comfort effects are important, and ample time is available, use a heated-type instrument.

"3. For relative measurements, adhere to a single instrument, selecting one that will cover the entire velocity range.

"4. For absolute measurements (i.e., those in which an accurate result in feet per minute is required), check the measurements by using more than one type of instrument.

"5. Always take the average of several readings to represent the final result."

Acknowledgment

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[117] G. L. Tuve, D. K. Wright, Jr., and L. J. Seigel, *Trans. ASHVE*, **45**, 645 (1939).

Chapter Eleven

Occupational Dermatoses

LOUIS SCHWARTZ, M.D.

Occupational dermatoses include not only inflammations of the skin, but stigmata, traumatic injuries, chemical and thermal burns, ulcerations and proliferations caused by contact with physical and mechanical forces as well as with chemical substances encountered in the course of occupation.[1]

I. Historical Data

While Paracelsus and Agricola noted skin changes caused by salt compounds and ulcers among metal workers early in the sixteenth century, it was not until the beginning of the eighteenth century that a clear detailed description of occupational skin diseases was published. Bernardino Ramazinni (1633–1714) published *De morbis artificium diatriba,* in which he describes occupational skin diseases among bakers, millers, sievers of corn, washwomen, salt miners, hostlers, bath attendants, and midwives. He attributed the dermatitis among grain handlers to an invisible parasite, a most remarkable and accurate observation when it is considered that Ramazinni did not use a microscope. Ramazinni's book remained the standard text on occupational diseases for a century, although many of his conclusions are now known to be incorrect. It was not until near the end of the eighteenth century that further observations on occupational skin diseases were published. In 1775 Percival Pott, an Englishman, stated that cancer of the scrotum occurred in chimney sweeps because of the effect of soot-soiled clothing. There was a revival of interest in occupational skin diseases early in the nineteenth century.

In England, Robert Willan described dermatitis from shoemakers' wax. Thomas Bateman described dermatitis caused by sugar and spices. He also described vesicular and pustular eruptions caused by lime. C. Turner Thackrah described dermatitis among tobacco workers and laid particular stress on personal cleanliness as a preventive of occupational dermatitis.

In France during the same period, Alibert described the dermatoses occurring

[1] General Reference: L. Schwartz, L. Tulipan and S. Peck, *A Textbook of Occupational Diseases of the Skin.* 2nd ed., Lea & Febiger, Philadelphia, 1947.

among outdoor workers, caused by excessive exposure to sunlight, and the occurrence of favus among animal handlers. Rayer described pustular eruptions due to arsenic and also stated that cowpox and glanders can be transmitted to man. Ibrelile observed that infested hides can transmit anthrax to man and advocated their sterilization with boiling water. Other French dermatologists and the occupational dermatoses described by them during this period were: Potton, who described dermatitis among silk winders; Lespian, dermatitis caused by coal tar; Recourt and Chevalier, dermatitis caused by potassium bichromate. Bazin in 1862 published a classification of the causes of occupational dermatitis.

In Germany the outstanding contributors to the literature on occupational dermatoses during the nineteenth century were Casanave, Schedel, Von Blandit, Hebra, Eulenberg, and Hirt.

European legislators about this time inaugurated compensation laws first for industrial accidents, then for certain industrial diseases including dermatoses. After 1900 the interest in Europe concerning occupational dermatoses increased and there were noted contributions to the literature by such eminent dermatologists as Blaschko, Jadassohn, Bloch, Mayer, Oppenheim, McLeod, Sequira, Percival, and Prosser-White.

In the United States there was but little interest in occupational dermatoses before World War I. There were only a few scattered contributions by a few American dermatologists, Hazen and Lane especially.

During and after World War I there was a great increase in industrial activity in the United States, resulting in more occupational dermatoses and the subject became of greater interest to dermatologists. Contributions to the literature were made by such men as Gardner, Fordyce, Lane, Foerster, Downing, White, Sulzberger, and others.

In 1928 the United States Public Health Service organized a section for the study of occupational dermatoses. Since then interest in the subject has increased greatly in the United States; the literature now abounds with new observations and our compensation laws are including occupational dermatoses among the compensable diseases. At the present time thirty states have laws under which compensation for certain occupational dermatoses may be obtained.

II. Incidence

The records of state boards of health and state compensation boards have been showing a yearly increase in the number of cases of occupational dermatoses. This is largely the result of educational work among physicians and enforcement of reporting laws. For instance, in 1933, the Connecticut compensation board reported 386 cases of occupational dermatoses and none were reported by physicians, whereas in the month of December 1943 alone there were reported nearly 400 cases, and during all of 1943 nearly 2000 cases. Of the 2000 there were less than 300 reported by the compensation board, showing that the number of cases of occupational dermatitis sufficiently severe to cause absence from work of one week or more is not increasing, but that physicians are reporting the cases they are treating. California in 1933

reported 1150 cases of occupational dermatoses whereas in 1943 there were close to 5000 cases reported. The reasons are the same as given for Connecticut.

Conservative estimates of an annual incidence of 30,000 cases of occupational dermatoses in the United States are now known to fall far short of the actual number. Our examinations in factories show that, any time that a survey is made, more than 1 per cent (sometimes 10 to 15 per cent) of all the workers have occupational dermatoses. Of 20,000,000 workers this would give a conservative estimate of at least 200,000.

The annual loss in time from work plus cost of medical care and compensation for occupational dermatoses approximates 100 million dollars annually.

III. Causes of Occupational Dermatoses and Their Classification

The most frequent cause of occupational dermatoses in the United States is petroleum oils and grease. This is not because these are more powerful skin irritants than other chemicals, but because more workers are exposed to their action than to any other class of irritant chemicals. Practically all machine tools use cutting oils and lubricants. Next in etiologic frequency are the volatile solvents, alkalies, plants, and materials encountered in metal plating. With our entrance into World War II, dermatitis from explosives ranked in frequency with those in the above list. This, of course, ceased with the war.

In the course of our studies in the various industries we have found the highest incidence of occupational dermatoses among workers engaged in the manufacture and use of the resins containing formaldehyde, such as the phenol-formaldehyde resins, and among workers engaged in the manufacture of chemicals and dyes.

A. PREDISPOSING CAUSES

The cornified cells of the epidermis, the pigment, and the secretions of the skin glands constitute the defense of the skin against the action of external irritants. The cornified cells are attacked by strong alkalies, but will withstand the action of fairly strong acids and some solvents.

The secretions of the skin consisting principally of water, liquid waxes, and cholesterol act as diluents to water-soluble skin irritants as well as forming a protective coating against them. The pigment of the skin, melanin, protects against the action of light. The perspiration, however, sometimes aids the action of irritants by macerating the skin, and by dissolving solid irritants and thus permitting them actually to come in contact with the skin.

The openings in the skin, the ducts of glands and the hair follicles, are the vulnerable portions because through them irritant chemicals that do not affect the cornified cells may penetrate the skin. Thinning of the cornified layer and breaks in the skin such as are caused by wounds and lesions of skin diseases also offer portals of entry for external irritants.

The following are the principal factors concerned with predisposition to the action of external irritants and therefore to occupational dermatoses.

1. Race

Certain industries such as those manufacturing or using coal tar and its heavy distillates prefer to employ Negroes because they seem to be less susceptible to skin irritation caused by these substances. This does not mean that Negroes employed in such industries do not have dermatitis. We have seen keratotic changes and even photosensitivity in the skin of Negroes working with coal tar. We know that corrosives, strong alkalies, and volatile solvents cause dermatitis in Negroes as well as in whites.

However, different types of skin do differ in sensitivity to external irritants. Blonds are more susceptible to solar radiation than are brunettes. Oily skins withstand the action of volatile solvents better than do dry skins. Hairy skins are more apt to develop oil folliculitis than are hairless skins. Different portions of the skin of the same person differ in susceptibility to external irritants. Where the keratin layer is thinnest, there is the greatest susceptibility. The palms and soles are but seldom affected by industrial skin irritants. Trinitrotoluene is an exception to this.

2. Age

Young workers, new on the job, are more frequently affected with acute occupational dermatoses. This may be because they may be less careful than older workers or because they may have not yet become "hardened." If new workers develop dermatitis they do so usually during the first month after beginning work. The chronic allergic eczematoid type of occupational dermatitis usually affects workers who have worked for many years without trouble. It seems as if they had lost their "hardness."

3. Sex

Women, as a rule, are more cleanly in their habits than men. Therefore they do not develop severe occupational dermatoses as frequently as do men. Women notice and ask treatment for the slightest skin irritation, such as most men will not even notice. Hence, the women workers may seek medical advise for skin irritations more frequently than men. The records of compensation boards show far fewer claims for compensation among women than among men, this despite the fact that women are now engaged in most occupations in which there are marked skin hazards.

4. Season of the Year

Because less clothing is worn in warm weather and because there is more perspiration, occupational dermatitis is more prevalent in most industries during the summer than the winter. On the other hand, occupational dermatitis may be more prevalent in the winter in those industries where cleansing showers after work are required in order to prevent dermatitis; this happens because workers are less likely to take the required shower after work in cold weather.

5. Perspiration

While perspiration acts as a diluent for external irritants, it also may act as a wetting agent and enable solid irritants to wet or contact the skin and so cause

dermatitis. Excessive perspiration, especially if combined with friction, may so macerate the skin as to make it specially vulnerable to the action of irritants. It may also cause such changes in a chemical as to make it a skin irritant: for instance, perspiration slakes dry lime forming calcium hydroxide, a powerful alkali, and generating heat, thus causing either ulcers or dermatitis. The pH of the perspiration affects its ability to act as a solvent and hence may serve as a predisposing cause of dermatitis; thus, the diet may predispose to occupational dermatitis as it influences the pH of the perspiration.

6. Presence of Skin Disease

Workers having other skin diseases are more likely to be affected with industrial dermatitis because open skin lesions offer but little resistance to the action of external irritants. A person who is allergic to one substance is not necessarily more likely to become allergic to other dissimilar substances than one who is not allergic at all. In other words, mono allergy does not predispose to poly allergy. If this were not true, there would be a large percentage of the population who would be polysensitive because certainly a large percentage of the population is sensitive to some one substance.

7. Uncleanliness

This is probably the most important predisposing cause of occupational dermatitis. Uncleanliness of the working environment exposes the worker to large doses of external irritants. Personal uncleanliness not only does the same, but also permits the external irritants to remain in prolonged contact with the skin. Workers wearing or carrying to their homes their dirty work clothes may even cause dermatitis in other members of the family who come in contact with the soiled clothes, or even among unsuspecting laundry workers who clean them.

8. Allergy

Hypersensitivity may be divided into two groups: (*1*) hypersensitivity caused by defects in the defense mechanism of the skin that permit the easy entrance of external irritants; and (*2*) hypersensitivity acquired by exposure, this sensitivity requiring a period of incubation of five or more days after exposure before manifesting itself by a dermatitis upon continued exposure—a phenomenon requiring the action of the mechanism of immunity. If hypersensitivity, acquired without recognizable breaks in the defense mechanism of the skin, is the only true allergy, then allergy in normal times causes less than 20 per cent of all occupational dermatoses. In times of war the incidence of allergic dermatoses is higher because most of the dermatitis caused by explosives is allergic. Most of the cases of acute allergic dermatitis occurring among new workers get well, because upon continued exposure they become "hardened." In other words, the first exposure sensitizes after a period of incubation; a continued exposure causes an eruption; and in most cases continued exposure for two weeks or more causes a "hardening" or hyposensitization. This hardening is not absolute, because exposure to higher concentrations may again

bring out an eruption, but in most instances "hardening" will also develop to this higher concentration, or greater exposure. This hyposensitization lasts only a limited time after exposure ceases, in some cases only two to four weeks, so that if the worker is re-exposed after this time he again goes through the same process before becoming hyposensitive or "hardened."

B. ACTUAL CAUSES

The actual causes of occupational dermatoses may be divided into mechanical, physical, and chemical.

1. Mechanical

Mechanical causes of occupational dermatoses, consist of pressure; friction causing skin irritation, calluses, and keratogenic changes; cuts and abrasions, which may become the sites of secondary infections or sites of such skin diseases present on other parts of the body as psoriasis and lichen planus (Koebner phenomenon).

2. Physical

Physical causes of occupational dermatoses are heat, cold, and radiation. Heat may cause excessive perspiration at sites of friction such as the axillae, the groin, underneath the breasts, and so on, with resulting intertrigos. It may also cause burns and telangiectases such as occur in stokers and still cleaners. Cold may cause frostbite among outdoor workers. Radiation from the sun causes sunburn, herpes, and epithelioma, as occurs among sailors and farmers. Electricity can cause occupational burns among linemen. Radium has been known to cause cancer among workers who mine pitchblende and other radioactive ores, luminous-dial painters, radiologists, and technicians using radium. X-rays have caused occupational burns and cancer among makers of x-ray apparatus and among physicians and technicians.

3. Chemical

Chemical causes of occupational dermatoses may be divided into primary irritants and sensitizers and each of these may again be divided into inorganic and organic.

Primary irritants. A primary skin irritant is one that causes dermatitis by direct action on the skin at the site of contact if it is permitted to act in sufficient concentration or quantity for a sufficient length of time. A primary skin irritant has a direct chemical or physical action on the skin, combining with it to form new compounds or abstracting from the skin some of its essential constituents. Some primary skin irritants may be sensitizers also.

Action of primary irritants. Primary skin irritants affect the skin in one or more of the following ways:

(*a*) They dissolve the keratin (alkalies, soaps, sulfides); (*b*) dissolve or emulsify fat and cholesterol (the organic solvents and alkaline detergents); (*c*) precipitate the proteins (tanning agents and salts of heavy metals); (*d*) are oxidizers (bleaches and

per salts); (*e*) are dehydrators (inorganic acids and anhydrides and hygroscopic chemicals); (*f*) are reducing agents (some organic acid and sulfides); (*g*) are keratogenic in their action (coal tar and petroleum).

Sensitizers do not necessarily cause demonstrable skin changes on first contact, but effect such specific changes in the body or skin that, after five days or more, further contact on the same or other parts of the body will cause dermatitis.

Primary Irritants

Inorganic acids	Alkalies	Elements and salts
Arsenious	Sodium and potassium	Aluminum sulfate
Chlorosulfonic	hydroxide	Ammonium
Chromic	carbonate	Antimony sulfide
Hydrofluoric	peroxide	chloride
Hydriotic	silicate	oxide
Hydrobromic	cyanide	Arsenic, arsenates, and alkaline earth salts of arsenious acid
Iodic	sulfide	Bromine
Hydrochloric	hypochlorite	Cadmium cyanide
Hydrofluosilicic	Calcium oxide	Chlorine
Nitric	hydroxide	Chromium and alkaline bichromates
Perchloric	hypochlorite	Iodine
Phosphoric	chloride	Mercury, mercuric chloride, nitrate, cyanide
Stannic	cyanamide	Phosphorus
Sulfamic	Cement	Potassium
Sulfuric	Soaps	Radium
Sulfurous	Trisodium phosphate	Selenium
Tungstic		Sodium
		Tin chloride
		Zinc chloride

Organic acids and anhydrides		Materials having keratogenic action
Acrylic	Lactic	Radiation:
Acetic	Maleic	Solar[a]
Carbolic	Naphthenic	X-ray, radium, and radioactive substances[b]
Chloroacetic (mono-, di-, tri-)	Orthochlorobenzoic (para)	Heat: kangri cancer
Cresylic	Oxalic	Trauma:
Formic	Phenolsulfonic	Long-continued irritation
Acid H. (aminonaphtholdisulfonic)	Phthalic	Cancer arising from cicatrices
Acid J. (aminonaphtholdisulfonic)	Salicylic	Soot[c]
Acid Koch (naphthylaminetrisulfonic)	Tobias acid (2-naphthylamine-1-sulfonic acid)	Petroleum: crude and high-boiling fractions
	Vinylacetic	Coal tar: crude and high-boiling fractions
	Vinylacrylic	Benzidine
Aldehydes and amines		α = Naphthylamine
Formaldehyde and most other aldehydes are primary irritants, as are most of the amines		β = Naphthylamine
		Arsenic
		Some synthetic dyes, such as amidoazotoluene have been reported to cause cancer

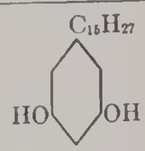
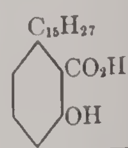
Primary Irritants (Continued)

Solvents		
Turpentine group; compn. varies, mainly, dextro and levo pinenes: Turpentine Wood spirit Pine oil Pine needle oil Oil of spike Terpineol Rosin spirit Tar spirit	*Petroleum solvents and oils* Gasoline Cymogene or rhigolene Pentane Petroleum ether Petroleum spirit (ligroin) Benzine White spirit Petroleum oils	*Chlorine derivatives:* Methylene chloride Chloroform Carbon tetrachloride Dichloroethylene Trichloroethylene Perchloroethylene Tetrachloroethane Pentachloroethane Monochlorobenzene Dichlorobenzene
Coal tar group: Benzol Light solvent naphtha Heavy solvent naphtha Xylol Cyclohexane Tetralin Decalin	*Esters:* Methyl acetate Ethyl acetate Amyl acetate Butyl acetate Methyl formate Ethyl formate Butyl formate Amyl formate	*Resin solvents:* Dichlorohydrin from glycerol + hydrochloric acid Epichlorohydrin from glycerol + hydrochloric acid + acetic acid
Alcohols: Methyl alcohol Ethyl alcohol Butyl alcohol from mash Amyl alcohol from petroleum Propyl alcohol from petroleum Benzyl alcohol from toluene Cyclohexanol from cyclohexane	*Ketones:* Acetone Methyl acetone Methyl ethyl ketone Methyl cyclo hexanone	Carbon bisulfide

[a]Outdoor workers. [b]Physicians, technicians. [c]Chimney sweeps.

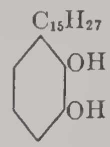
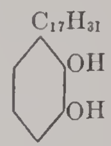
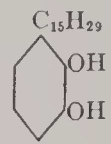
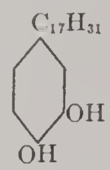
Plants causing dermatitis (primary irritants and sensitizers). Most plants which cause dermatitis are sensitizers. The principal irritants in the plant group belong to the family *Anacardiaceae.* They produce allergic dermatitis and many workers develop "hardening" upon continued occupational exposure.

Irritant Anacardiaceae (According to Haack)

Botanical name	Encountered as	Active ingredients	Formula[a]
Anacard. occidentale Linn.	Cashew nut shell	Cardol and Anacardic acid	 

(*continued*)

Irritant Anacardiaceae (Continued)

Botanical name	Encountered as	Active ingredients	Formula[a]
Pentaspadon Motleyi Hook f.	Japan and Chinese lacquers	Cardol	
Rhus vernicifera		Urushiol	
Rhus succedanea Linn. f.	Indo-China lacquer	Laccol	
Rhus ambigua Lav. (= *R. orientalis Schn.*)		Laccol	
Rhus toxicodendron Linn. (= *R. radicans* = *R. diversiloba*)	Poison ivy	Urushiol	
Rhus venenata (= *R. vernix*)	Poison sumac	Urushiol	
Semecarpus anacardium Linn. f.	Marking nut	Bhilawanol (= urushiol)	
Semecarpus heterophylla Bl.		Renghol	
Semecarpus albescens Kurz.			
Semecarpus cassuvium Roxb.			
Semecarpus Forsterii Bl.			
Semecarpus vernicifera Linn.	Formosa lacquer	Laccol	
Mangiferra indica Linn.			
Mangiferra caesia Jack.			
Mangiferra foetida Lour.			
Mangiferra odorata Griff.			
Gluta rhengas Linn.		Renghol	
Gluta velutina Bl.			
Melanorrhoea usitata. Wall.	Burma lacquer	Thitsiol	
Melanorrhoea wallichii Hook f.			
Melanorrhoea curtisii Oliv.			
Melanorrhoea tomentosa Hook f.			
Melanorrhoea laccifera Pierre.			
Buchanama arborescens Bl.			
Buchanama velutina Bl.			

[a]It will be noted that urushiol, laccol, and renghol are similar compounds. Cardol and thitsiol differ in molecular structure.

Dermatitis has been reported from more than 500 different plants; of which the most frequently reported are:

Primrose
Nettle
Spurge
Daffodil
Tulip
Cinnamon
Mango
Fig

Prickly pear
Asparagus
Chrysanthemum
Hops
Vanilla
Marigold
Cow parsnip
Wild carrot

Satinwood
Mahogany
Boxwood
Brazilian walnut
Cocobolo
Teak
Chestnut

Dermatitis is of frequent occurrence among fruit and vegetable packers and canners. The following fruits and vegetables have been reported to cause dermatitis:

Oranges
Lemons
Grapefruit

Peaches
Figs
Tomatoes

Pineapples
Mangoes
Carrots

Lettuce
Hops
Celery

Sensitizers. It is impossible to give a complete list of sensitizers because some people may be sensitive to substances to which the large majority are not, for instance, wool, heat, cold, silk, etc. Substances that sensitize to sunlight are called photosensitizers.

Photosensitizers

Coal tar	*Daucus carota* (wild carrot)
Pitch	*Tribulus terrestes* (puncture weed)
Asphalt	*Trifolium hybridum* (alsike clover)
Creosote oil	*Hypericum perforatum* (St. John's wort)
Fluorescin	*Hypericum crispum* (St. John's wort)
Rhodamine N.	*Medicago denticulata* (bur clover)
Bergamot	*Nolina texana* (bunch grass)
Figs	*Polygonum persicaria* (lady's thumb)
Agave lecheguilla	*Tetradynia canescena* (rabbit bush)
Fagopyrum esculentum (buckwheat)	*Tetradynia glabrata* (rabbit bush)
Fagopyrum tataricum (India wheat)	

4. Biologic Agents

Biologic agents may be causes of occupational dermatitis. Bacteria may infect occupational wounds. Erysipeloid, caused by the bacillus of swine erysipelas, occurs among butchers, bone button makers, and fishermen. Butcher's pemphigus is a rare occupational disease. Impetigo, cowpox, anthrax, glanders, actinomycosis, foot and mouth disease, all may be contracted occupationally from infected animals. Verruca necrogenica, or tuberculous warts, occurs among butchers, and postmortem attendants.

The accompanying tables list occupational dermatoses that may be caused by parasites and fungi.

Parasites

Dermatosis	Causative organism	Vector
Scabies	*Acarus scabei*	Clothing, as in barracks
Pediculosis	*Pediculosis pubis*	Clothing, as in barracks
Pediculosis	*Pediculosis corporis*	Clothing, as in barracks
Mange	*Acarus sarcoptes* (or demodex)	*Animals*
Ground itch (uncinariasis, aukylostomiasis)	*Aukylostomaduodenale*, or *Necatur americanus*	Earth infested with hookworms
Grain itch	*Pediculoides ventricosus*	Grain or straw
Barley itch	*Sphoerogyna cerealella*	
Grocer's itch	*Carpoglyptus passularum*, *Tyroglyphus*	Figs, dates, prunes, cheese
Rat mite dermatitis	*Liponyssus bacoti*	
Copra itch		Beetles and parasites
Linseed itch		
Hog itch	*Ascaris*	Hog intestines
Tick bites	*Ixodes* (cattle ticks, wood ticks)	Cattle, woods
Harvest itch	Chiggers, *Leptus* (*Trombicula*) *irritans*	Grass or grain
Sand flea bites	Chigoes	
Fowl mite itch (Gamasoidosis)	*Dermanyssus avium*	Mite-infested birds or bird homes

Fungi

Fungi	Occupation
Yeasts	Bakers, dishwashers
Monilia	Dishwashers, scrubwomen, fruit canners
Dermatophytes	Animal handlers; fur, hide, and wool workers; barbers, beauticians, bath attendants
Sporotrichum	Horticulturalists
Blastomycetes	Horticulturalists
Actinomycetes	Animal handlers

The following moths or their caterpillar stages have been reported to have caused dermatitis among horticulturists and farmers:

Moth	Action
Brown-tail (*Euproctis*)	hairs irritate
Gold-tail (*Liparis chrysorrhea*)	hairs irritate
Goat (*Cassus ligniperda*)	secretes formic acid
Puss (*Cerura vinula*)	secretes irritant
Fox (*Chenilles processionnaires*)	hairs irritate

IV. Clinical Types of Occupational Dermatitis

Occupational dermatitis may assume the following forms:

1. Acute eczematoid dermatitis, which is characterized by erythema, edema, papules, vesicles, crusts, and desquamation. It is usually the result of a primary skin irritant or of an initial allergic dermatitis.
2. Chronic fissured eczematoid dermatitis, characterized by erythema, lichenization, cornification, and fissuring. It is usually the result of unresolved acute cases or the prolonged action of mild dehydrators, fat solvents, soaps, and detergents.
3. Folliculitis and acneform lesions, characterized by plugged sebaceous glands and suppurative inflammation of hair follicles. It is usually due to exposure to coal tar, petroleum oils, or solid chlorinated hydrocarbons.
4. Epidermal proliferation, which may be malignant or benign, characterized by keratosis, papillomata, and epitheliomata. It is usually caused by exposure to coal tar and its heavier distillates or to crude petroleum oil.

V. Diagnosis of Occupational Dermatoses

Dermatoses affecting workers are not all occupational. Workers may develop dermatoses from causes that have no connection with their occupations. It is often necessary to prove or disprove an occupational etiology. This is necessary not only for the purposes of treatment and prevention, but also because of compensation.

The diagnoses of occupational dermatoses are made on the following criteria:

1. History must show: (*a*) dermatitis did not antedate employment; (*b*) dermatitis developed during period of industrial exposure or about 10 days after employment (incubation period); (*c*) dermatitis improves away from exposure and exacerbates on re-exposure.
2. Site of eruption: (*a*) first appears on exposed parts or sites of friction; (*b*) covered parts

affected by penetrating dusts, fumes, and soiled clothes; (c) distant parts affected in allergic cases after incubation period.

3. Appearance of lesion: may be characteristic of class of irritant but not of particular irritant.
4. Patch tests: must be intelligently performed; results properly read and evaluated.
5. If a doubtful case shows no marked improvement two months after exposure ceases it is probably not of occupational origin, or is being irritated by a nonoccupational irritant.

Occupational dermatoses may have to be differentiated from nonoccupational skin disorders. The ordinary nonoccupational dermatoses such as psoriasis, lichen planus, acne vulgaris, erythema multiforme, pityriasis rosea, and so forth offer dermatologists no difficulties in differential diagnosis; but to differentiate from contact dermatitis caused by irritants encountered outside of the occupational environment often requires considerable investigation. The occupational history must be carefully considered and correlated with the appearance and site of the eruption. The occupational process and the chemicals contacted must also be correlated with the site and appearance of the eruption. It is often necessary to perform patch tests with sensitizing substances that the worker contacts. (*Patch tests with strong primary irritants should never be made.*) Although there are exceptions a good rule is that occupational dermatitis improves when the worker stays away from work and gets worse if he returns to work (except where "hardening" has occurred).

The lesions of dermatophytosis and their allergic eruptions, called phytids, also offer some difficulties in differential diagnosis, especially when the lesions are on the fingers, hands, and arms. A few simple differential points follow. Occupational dermatitis rarely occurs as deep-seated vesicles on the palms or soles; the phytids often occur as such. The phytids are accompanied by fungus infections between the toes, or on the feet, or the axillae, or groin, and careful examination will in many cases result in demonstrating the causative fungus. The trichophyton test is positive when a fungus infection or phytid is present. It is negative in about 50 per cent of cases where there are no clinical evidences of fungus infection. The patch test with the occupational causative substance is positive in the active stage of the eruption. It is negative if the eruption is purely of fungus origin.

Fungus infections and phytids are in most instances independent of working conditions, and their improvement does not depend on absence from work. In differential diagnosis of occupational from nonoccupational dermatoses it is usually safe to say that if a supposed case of occupational dermatitis does not recover or markedly improve after two months absence from work, it is probably not connected with the occupation (unless it is overtreated or nonoccupationally irritated).

We must not lose sight of the fact that it is entirely possible for a worker to have a fungus infection and an occupational dermatitis at the same time.

THE PATCH TEST IN INDUSTRY

There has been much controversy regarding the value, proper technique, and interpretation of patch tests.

The patch test was devised by Jadassohn almost fifty years ago for demonstrat-

ing the causes of contact dermatitis. In the United States the patch test was not widely used in industry, nor was its practical value appreciated, until after the United States Public Health Service called attention to the prevalence of occupational dermatitis, and to the actual chemicals causing it, and to the value of patch tests in the differential diagnosis between occupational and other sources of contact dermatitis.

At first the patch test was used as a means of diagnosing contact dermatitis and of determining the actual causative chemical irritant. Since dermatitis among the general public has on many occasions been found to be caused by irritant chemicals contained in garments and cosmetics, manufacturers have taken advantage of the patch test to determine the possible skin irritating or sensitizing properties of new products before placing them on sale to the public (prophetic patch test).

It has even been proposed by some enthusiasts to use the patch test as part of the pre-employment examination with the idea of weeding out those workers who might develop occupational dermatitis. The fallacy in the proposal is that most workers develop their occupational dermatitis either by contact with a primary irritant or by acquiring an allergy while actually employed. Therefore, pre-employment patch testing could not weed out those who would become sensitized.

It is now universally accepted that the patch test is a valuable diagnostic procedure. Its value in preventing possible outbreaks of dermatitis from the use of materials containing new chemicals is just becoming recognized.

1. Technique

Before attempting to describe the methods used for patch testing, we must clearly distinguish between substances that are primary skin irritants and those that we shall call sensitizers. It is obvious that a concentrated solution of a strong acid or alkali will burn or inflame any skin, the degree of injury depending on the concentration of the irritant, the amount applied, the duration of its action, and the area of skin to which it is applied. Such chemicals actually form chemical combinations with the skin, and can be called primary irritants. There is another class of chemicals that will cause inflammation of the skin if applied for a sufficient length of time, that is, the strong solvents such as gasoline, carbon tetrachloride, chloroform, and so on. These substances abstract from the skin some of its essential components, such as the fats, resulting in inflammatory reaction. Other chemicals have different actions on the skin, such as protein precipitants, oxidizers, keratin solvents, reducing agents, and so forth; all these are primary irritants.

It is obvious that patch testing with strong concentrations of known primary irritants will result in reactions on any skin. This does not mean that patch testing should not be performed with dilute solutions of chemicals that in strong concentration are primary irritants. There are published lists of concentrations of chemicals that dermatologists have used as patch tests to determine hypersensitivity. The use of these concentrations, together with the time they are to remain on the skin, is an attempt to avoid the primary irritant action of the chemical.

While the majority of occupational dermatoses are caused by primary irritants, about 20 per cent are caused by substances that do not have a primary irritant action on the skin. These chemicals that are not primary irritants are responsible for by far the large majority of cases of contact dermatitis among the public caused by wearing apparel, cosmetics, ornaments, etc. They induce a specific skin allergy and thus cause dermatitis. They are called sensitizers. It is well known that many chemicals that are primary irritants are also sensitizers, for instance formaldehyde, bichromates, mercuric salts, phenols, and so forth.

The ordinary diagnostic patch test consists in applying a small portion of the suspected substance to a site of normal skin of the patient. This is covered with innocuous impermeable material, which is then sealed to the skin by adhesive plaster. There have been many modifications proposed in order to overcome certain objections.

The diagnostic patch test is performed in the following manner with liquids: saturate a piece of four-ply gauze about ¾ in. square, and apply it to uninflamed skin on the arm or back. The liquid should not be permitted to trickle from the patch site. For insulation a 1½-in. square piece of nonwaterproof cellophane is used. (Waterproof cellophane consists of regenerated cellulose coated with a water-insoluble resin.) This is sealed to the skin with a piece of adhesive plaster about 3 in. square. When smaller pieces of adhesive plaster are used patches are often lost or there is insufficient contact of the test substance with the skin. The reactions that may result from the adhesive plaster are separated from those resulting from the test substance by the uninflamed skin which is in contact with the cellophane only. In performing a number of patch tests, care should be taken to avoid overlapping of adhesive plaster, which will cause intensification of the adhesive plaster reaction.

In performing patch tests with powders, the powder is placed on a piece of gauze in order to keep the reaction localized. If the gauze is moistened it holds the powder better than when dry.

In patching with solids it is not necessary to use gauze. When solids insoluble in water are used for patching we have found it best to dissolve them in a solvent making a saturated solution and wetting a piece of gauze with this solution. The gauze is then allowed to dry before placing it on the skin. This procedure deposits the precipitated finely divided substance on the gauze and thus brings about better contact with the skin. When the insoluble solid is of a resinous character the solution may be painted directly on the skin, the solvent allowed to evaporate, and the cellophane and adhesive plaster applied. In such cases if the resin adheres firmly to the skin it is not necessary to cover it with the cellophane and adhesive. The technique of patching with ointments is the same as for liquids.

While solvents are primary skin irritants they sometimes also act as sensitizers. When it is desired to find out whether a solvent is causing dermatitis by its action as a sensitizer, patch tests may be performed as follows: mix equal parts of the solvent with equal parts of a bland oil such as liquid petrolatum or corn oil, in order to buffer its primary irritant action, and patch as for liquids.

It is usually sufficient to leave the patch on for 24 hours, but sometimes when patching with low concentrations or with weak sensitizers it may be necessary to leave the patch on for three or four days. (Do not leave on more than five days; the patient may by that time become sensitized to the patch.) This is especially true of fabrics that contain no strong irritants and to which most people do not react. The reactions should be read not only upon the removal of the patches but every day for at least five days thereafter. This is of special importance in testing fabrics.

It is sometimes advisable to use a so-called artificial perspiration to moisten the test substance because the H-ion concentration of the perspiration, especially in such areas as the axillae, may play a role in the solubility of the irritant under investigation. The pH of axillary sweat is usually on the alkaline side and that on the body proper is on the acid side; pH can vary from 5 to 8. To approximate the pH of the perspiration, acidify water with acetic acid and alkalinize another sample with ammonia.

2. *Interpretation and Reading of Patch Tests*

It requires considerable experience to interpret correctly the reactions produced by patch tests. Since the patch test was first introduced by Jadassohn and Block, grading of the patch test reactions has been attempted in ranges between 1+ to 4+. For instance, a 1+ reaction indicated an erythema on the area of skin to which the chemical was applied; a 2+ reaction indicated erythema and edema; a 3+ reaction indicated an erythema, edema, papules, and a few vesicles; a 4+ reaction indicated erythema, edema, many vesicles, and even ulceration.

Such a method of recording a positive patch test is useful perhaps in indicating the degree of sensitivity to the specific concentration and amount of the chemical used. Additional information and interpretation can be obtained if patches with differing concentrations are applied. The degree of reaction will be greatest at the site of greatest concentration. Reactions that are not present when the patch is removed but become manifest less than five days after the patch was applied are delayed reactions. Delayed reaction means either that there is present a low degree of specific sensitivity or that a weak concentration of the sensitizer was used.

The true allergic reaction as a rule increases rather than decreases in intensity for 24 to 48 hours after the patch test is removed. Reactions of primary irritation with few exceptions tend to subside after the removal of the irritant.

The evaluation of a weakly positive reaction (1+) depends a great deal on the experience of the one reading the patch test. In dealing with a fabric or other substances containing a weak concentration of a sensitizer, a 1+ or 2+ reaction is significant. This is especially true in industry where not only is a dermatitis due to a contact with the sensitizer in low concentration, but where there may also be the added factor of friction, with an exposure to large amounts of the chemicals, much more than is present in the patch test.

A positive reaction that cannot be reproduced with the same technique indicates that at the time the original patch test was performed the patient was sensitive

to the concentration and quantity of chemical applied. A 1+? reaction not persisting for 24 hours is probably a false positive. A negative patch test does not necessarily rule out the test substance as a causative agent. The negative reaction might be due to the fact that: (*1*) under the condition of the patch test the actual mechanism that produces the dermatitis is lacking, that is, the patch test does not equal working conditions; or (*2*) the patient is no longer sensitive; or (*3*) the actual sensitizer was not applied.

The impression seems widespread that patch tests should not be performed while an eruption is still present because a flare-up of the dermatitis might take place. The most favorable period, when a positive patch test can be expected, is at the time that the dermatitis is still present. A relative hyposensitivity may develop when the dermatitis disappears, with the result that the patch test would tend to be negative. Here, too, experience and judgment are necessary to choose the proper time for performing patch tests. Obviously, when dealing with a patient who has a generalized dermatitis it is better to wait until the eruption has improved before performing a patch test and, when it is carried out, a low concentration of the suspected chemical should be used. A generalized eruption may mean either that we are dealing with a high degree of sensitivity, or a massive exposure of a person who is only moderately sensitive.

In cases with true allergic dermatitis, the skin all over the body is sensitive and patch tests can be applied at any convenient site. The most rapid reaction, all other factors being equal, will take place in areas of skin where the keratin is thinnest. The thick keratin layer of the palms and soles not only explains the negative patch test that results at these sites, but is the main reason why contact dermatitis is rarely seen in these locations.

3. Complications of Patch Tests

Unless inadvertently a patch test is made with a primary irritant, even strongly positive reactions do not leave a scar. In the presence of marked hypersensitivity, patch testing with a fairly high concentration of the allergen may produce a skin reaction that spreads beyond the area of application of the patch, or it may elicit a generalized reaction. This generalized reaction may manifest itself either as a flare-up of existing lesions, reappearance of lesions that have already faded, or the appearance of a generalized eruption. Such a complication may occur even when a standard concentration of the sensitizing chemical is used for the patch test. This last, however, is rare. Toxic symptoms from absorption of the patch-test material are unlikely because of the small amounts of chemical used and the relatively small area of skin through which absorption is possible. However, such rare instances have been reported. Systemic symptoms such as a rise in temperature, adenopathy, and pain have sometimes occurred after patch testing.

Patch tests are of established value in the determination of the etiologic agents in dermatitis venenatum, and are accepted by many insurance companies and compensation boards as necessary steps in establishing a causal relationship.

Patch tests should not be performed with allergens with which the patient has not already come in contact and which he may later encounter frequently in the course of his daily life, because of the possibility of inducing a hypersensitivity, with a resultant dermatitis the next time he comes in contact with the allergen.

VI. Prevention of Occupational Dermatoses

There has not been as much attention paid to the prevention of occupational dermatitis as to the prevention of occupational poisonings, despite the fact that there is more time lost from work on account of occupational dermatitis than from any other occupational disease. It seems as if safety engineers think that the prevention of a mere "occupational itch" is not worth much thought, but often an "itch" is the first indication of the presence in the air of a systemic poison in toxic quantities. If a chemical irritates the skin, it may also affect the entire system. Protecting the skin may save the whole body.

Unlike the protective measures taken against systemic occupational diseases, which are practically the same for nearly all—reduction of the concentration of the poison in the air by enclosed processes and exhaust systems—the same method of prevention will not suffice for all of the various skin irritants encountered in our industries. There are many protective measures against the different sources of industrial skin irritants.

1. Pre-employment Examinations

Protective measures should begin in the pre-employment examination, when the skin of the applicant should be carefully examined, and the pathologic conditions found should be noted on the examination card. Applicants with skin eruptions should not be employed in occupations in which there is a marked skin hazard; for instance, those applicants having allergic eczemas should not be employed where there is a marked skin hazard from such well-known sensitizing chemicals as tetryl, fulminate of mercury, the picrates, TNT, formaldehyde and its compounds, some intermediates in synthetic dye manufacture, and others too numerous to mention.

Pre-employment patch testing for the purpose of discovering those workers who are allergic is not advisable. Because workers are usually not allergic to chemicals with which they have had no previous contact, very few allergies, if any, would be discovered by this method. Patch-testing workers with sensitizing materials may be the means of sensitizing them. Moreover, workers found by patch tests to be sensitive, and therefore rejected, may have a legal claim against the company for having been given a skin eruption that they otherwise would not have had.

Careful note should be made of the sites of acne vulgaris lesions on applicants for work in occupations in which they are to be exposed to such occupational acne producers as the solid chlorohydrocarbons, cutting oils, heavy coal-tar distillates, crude petroleum, and lubricants derived from it.

The presence of active mycotic infections on the feet and other parts of the body should be noted. If the applicants are otherwise employable, the fungus infections

should be treated while they are working, and the parts affected should be properly protected from the action of occupational irritants. If there are common shower baths in the factory, care should be taken to prevent the spread of fungus infections of the feet. This can be done by providing each worker with wooden-soled bathing slippers, and he should be instructed to wear these when going to the shower bath, while he is under the shower, and when coming from it. It is not sufficient to have antiseptic solutions in troughs into which the workers are required to step after they have taken their showers, because walking barefooted from the troughs to the lockers allows plenty of opportunity for them to pick up or spread the infection. The workers should also be instructed to dry the feet thoroughly and spread powder between their toes before putting on their stockings. The fungi do not grow in dry media. There are many powders on the market for this purpose, and most of them contain some antiseptic, such as oxygen in the form of perborates and peroxides, and other fungicidal chemicals.

Applicants who have dry skins should not be placed on jobs where they must immerse their hands in fluids that defat the skin, such as strong soaps, alkaline solutions, or the volatile solvents.

2. Ventilation

Efficient ventilating processes are of great value in protecting the workers from industrial skin irritants. See Chapter Ten.

3. Protective Clothing

Properly designed protective clothing is of great value in the prevention of occupational dermatitis. Closely woven cotton fabrics that are more or less impervious to dust are frequently used to protect workers from such irritant dusts as sodium carbonate, calcium cyanamide, and so forth. To give efficient protection, such fabrics must be frequently cleaned. Each worker should have at least two sets of work clothes, so that he will have a clean set to wear while the other is being laundered. It has been found best to have the management of the plant undertake the laundering of such clothes because the worker himself is often loathe to spend the money. In one plant where such was the practice, it was estimated that it cost the plant about ten cents per day to furnish daily clean work clothes for each worker.

Impervious materials, such as rubber, offer better protection against dusts than do fabrics, and they also give protection against irritant liquids. Rubber gloves, aprons, boots, and sleeves are impervious to water-soluble irritants. Rubber, however, soon deteriorates when exposed to alkalies, petroleum distillates, or the chlorohydrocarbon solvents. For this reason it is rather expensive to use in occupations in which it comes in contact with these chemicals. Synthetic rubbers such as neoprene, buna *N*, thiokol, and ameropol are more resistant to alkalies and oils than is natural rubber. However, workers often object to wearing rubber garments: some state that rubber causes them to perspire excessively, and some of them are allergic to compounds in the rubber.

We have found that some of the synthetic resin films, such as Pliofilm (manufactured by Goodyear Tire & Rubber Co., Inc.), Koroseal (manufactured by The B. F. Goodrich Co.), and Vinylite (manufactured by Union Carbide & Carbon Corp.), are impervious not only to dust and fumes, but also to strong acids, alkalies, and petroleum distillates.[2] These materials may be made into sleeves, aprons, hoods, and coveralls, and experimentally they have even been made into gloves. They are comparatively cheap, are noninflammable, may be easily cleaned with soap and water, and are transparent. This latter property removes the psychologic effect of feeling confined. It is true that these substances, like rubber, prevent the circulation of air on parts of the body that they enclose, but this can be overcome by placing vent holes in the upper parts of the sleeves and in the rear of the coveralls, where such holes are not likely to allow the entrance of irritants. We have found that these films also give good protection against vesicant gases. They can be made with tensile strength such that they will tear if caught by cogs before they can draw the arm of the worker into the machinery when worn as sleeves by machine operators.

These films are affected by trichloroethylene and carbon tetrachloride and, therefore, are not suitable for protection against these substances. The polyvinyl alcohols are proof against trichloroethylene and carbon tetrachloride. They are manufactured in the form of gloves and called by the trade name Resistoflex. The polyvinyl alcohols are affected by water and, therefore, Resistoflex gloves should not be exposed to it. They may be cleaned with the volatile solvents.

Cellophane can be plasticized with glycerin to form a pliable film capable of being made into protective clothing. Cellophane is not affected by acids or petroleum solvents, and is also good protection against vesicant gases. However, it is made hard and brittle by water, and is also highly inflammable. These disadvantages may be overcome by treating the cellophane film, while it is being manufactured, with ammonium sulfamate, which makes it flameproof, and by coating it with a water-insoluble resin, which makes it waterproof. Cellulose acetate films are water-insoluble and may make suitable protective clothing.

Leather gloves offer good protection against trauma and irritant or sensitizing solids and dusts. Leather gloves should be made of soft, pliable, washable leather, such as chamois. The seams should be finished and smooth. Coarse seams rub and irritate the skin, causing dermatitis not only by mechanical friction, but by rubbing into the denuded skin the irritant chemical particles that have fallen into the glove at the wrist opening. Gloves for the protection of the hands from irritant chemicals should reach well up the forearms and should be worn under impervious sleeves fastening at the wrists so as to prevent the entrance of irritant chemicals into the gloves. Aprons should reach well up to the neck and down below the knees. Aprons are of special value in protecting the body from cutting oil. The fact is again emphasized that in order for protective clothing to be really protective it must be cleaned daily and kept in good repair.

[2] L. Schwartz, H. Warren, and F. Goldman, *U. S. Pub. Health Repts.*, **55**, 1158 (1940).

4. Cleanliness

Cleanliness is by far the most important single measure for the prevention of industrial dermatoses. By cleanliness, we mean not only cleanliness of the person, but cleanliness of the room, the machines, and the clothes. Floors, walls, and ceilings of rooms in which there are industrial irritants should be wet-cleaned daily. Machines and tools on which industrial irritants are deposited also should be cleaned daily. Adequate washing facilities should be provided for workers handling industrial skin irritants. Workers whose clothes become soiled with industrial skin irritants should be compelled to take supervised shower baths after work, before leaving the factory. It may be necessary to have a double set of locker rooms to be sure that workers do not put on dirty clothes before going home. Care must be exercised so that the soaps and other cleansers used by workers to remove dirt, dyes, oils, etc., will not themselves cause dermatitis. Workers who become soiled with oils, greases, and dyes are likely, if left to themselves, to use the most available and most rapid-acting solvent to clean the skin. They do not stop to consider the irritant action of the cleanser. Many cases of dermatitis among workers have been caused by the cleansers used to clean up before going home. Safety engineers should see that workers use only such cleansers as will not act as skin irritants.[3]

An industrial cleanser for the normal skin should have the following qualities: it should be freely soluble in hard, soft, cold, or hot water; it should remove foreign soil, fats, and oils without harming the skin; it should not contain harsh abrasives or irritant scrubbers; it should be handy to use in cake form, or should flow easily through soap dispensers if in granulated powder, or liquid form; it should not deteriorate or become insect-infested.

For those occupations in which excessive scrubbing with such a soap is necessary in order to remove dyes or tenacious oil, it may be better to add to such a cleanser a small amount of alkali, such as trisodium phosphate. Whenever such alkali-reinforced cleansers are used, it is best to supply the worker with an emollient cream to be rubbed into the skin after washing so as to replace the fat removed by the strong cleanser.

Workers who have dermatitis, or sensitive or dry defatted skins, should not use the ordinary industrial cleanser previously described. It is better for them to use one of the soapless cleansers, the pH of which is 7 or less. Such a cleanser may consist of a neutral sulfonated castor oil containing from 1 to 2 per cent of the synthetic wetting agents. The cationic wetting agents also have marked germicidal powers and are said to leave persistent germicidal films on the skin. They have the disadvantage of being incompatible with soap.

5. Protective Ointments

While protective ointments are low on the list of preventive measures, they are often the only available means of protection. In most occupations the face can-

[3] L. Schwartz, *Med. Clinics N. America*, **26**, 1195 (1942)

not be covered by protective clothing. Often the work must be performed with bare hands, gloves being unsuited for the operation. Workers, as a rule, dislike to wear protective clothing but seem to have a particular liking for the use of protective ointments. When a protective ointment is used, the worker invariably washes it off with soap and water immediately after work, and so removes not only the ointment but whatever irritants there are on the skin. This washing after work adds considerably to the value of the protection supposedly given by the ointment.

There is no one formula for a protective ointment that will give efficient protection against all skin irritants. However, all protective ointments should have the following properties: they should be nonirritating and nonsensitizing; they should give actual protection from the irritant; they should be of such consistency that they can be easily applied; they should stay on while the worker is exposed to the irritant and yet be easily removable after work.

Protective ointments may be divided into six classes:

(*1*) The simple vanishing-cream type, which fills the pores with soap and facilitates the removal of soil when washing after work.

(*2*) The type that leaves a thin film of a resin or wax on the skin and thus prevents the irritant from touching the skin. This class may be subdivided into (*a*) water-soluble films, and (*b*) water-insoluble films. They may be in the form of ointments, emulsions, or solutions. This class of protectives is sometimes called the "invisible glove" type. The water-soluble film helps to protect against the volatile solvents and water-insoluble allergens such as TNT and tetryl. The water-insoluble resins and waxes are used to protect against water-soluble irritants. Shellac, benzoin, and nitrocellulose are the most frequently used resins in this form of protective. The water-soluble films used in protecting against water-insoluble allergens contain methyl cellulose, Irish moss, sodium silicate, tragacanth, acacia, or casein.

(*3*) Protective ointments that cover the skin and fill the pores with a harmless fat, which repels water-soluble irritants and prevents entrance into the pores of harmful petroleum oils, greases, and coal-tar derivatives, are used as protectives against cutting oils, greases, creosote, pitch, etc. They consist mainly of lanolin and sufficient castor oil to make the lanolin spreadable. The addition of a small amount of a wetting agent makes them easily removable with water, and the addition of a small amount of perfume masks the disagreeable odor of lanolin and castor oil.

(*4*) Protective ointments that contain a nonirritant chemical intended to detoxify the industrial irritant. For instance, such a protective cream against acids may contain soap and magnesium hydroxide intended to neutralize the acid.

(*5*) Protective ointments that cause inert powders to adhere to the skin, forming a protective covering against skin irritants. The powders may be calamine, zinc oxide, iron oxide, kieselguhr, bentonite, and so forth. The adhesive or binder may be any one of the resins mentioned in the "invisible glove" type of cream. These ointments are of value in protecting against allergenic substances.

(*6*) Protective applications against photosensitizing substances. These applica-

tions contain such physical light screens as methyl salicylate, aesculin, quinine, anthranilates, and tannates.

Most of the protective creams, emulsions, and lotions on the market can be classed under one of these six types of protective ointments.

VII. Treatment

Most of the cases of industrial dermatoses occur on new employees and they are usually mild in character. Such workers should be given a protective ointment to put over the exposed parts, proper protective clothing such as rubber gloves, aprons, and so forth, and should be kept on the job. Most of them will develop immunity. Those who do not should be given other work where they will not come in contact with the irritant. This usually effects a cure.

In applying medication to the lesions, only the mildest form of ointments or lotions should be used, such as aluminum acetate, boric acids, or calamine. Strong medicaments are apt to irritate the skin and cause more dermatitis.

Chemical burns should be immediately immersed or flushed with water to dilute and remove the irritant and then treated as any other burn. In some factories where there is a hazard from alkali burns, as for instance in viscose manufacture, a weak solution of acetic acid is kept handy so that it can be applied immediately to the places the alkali has touched. It is doubtful whether this practice is better than flushing with plenty of water. Acid splashes are treated in some factories with applications of sodium bicarbonate solution or lime water.

Ulcers resulting from such corrosives as chromic acid and chromates, zinc chloride, and fluorides, are best treated by thorough curettement of the base, followed by aseptic dressings.

No general rules can be given for the treatment of the chronic eczematoid types of occupational dermatitis. The cases should be treated according to the stage and extent of the lesions, the condition of the patient, and the complications present.

VIII. Occupational Cancer

Workers exposed to soot, pitch, coal tar, crude petroleum from certain localities such as Scotch shale oil, x-rays, radium, and excessive solar radiation, have a high rate of skin cancers.

Soot. Cancer of the scrotum among chimney sweeps was reported in England as eight times more prevalent than among the general population. It is caused by rubbing the soot into the scrotum as the sweep is squeezed when descending the chimney. It is practically nonexistent in other countries and is on the decline in England.

Coal tar. The heavy coal-tar distillates and pitch are the most frequent causes of occupational cancer. In the United States more than 90 per cent of all reported occupational cancers are caused by coal tar and its heavy distillates. The rate of skin cancers among workers with coal-tar pitch is high; the author found 5 cases

among 100 workers. Tar and pitch from gas works are more carcinogenic than tar and pitch from coke ovens. Road builders, roofers, conduit makers, and briquet makers are some of the workers outside coal tar and gas plants who handle coal-tar products and are often affected with skin cancers.

Petroleum. Workers in petroleum fields, especially where the crude oil is highly carcinogenic, are subject to occupational skin cancers. Shale-oil workers are said to have a carcinoma incidence of 1 per cent annually. Pure medicinal petroleum oils are not carcinogenic. Treatment with sulfuric acid during the refining process destroys the cancer-producing principle. Mule spinner's cancer of the scrotum has not been observed to be caused by spindle oils of American origin. It has been reported in England and is caused by friction of the oil-soaked clothes against the scrotum of workers on mule spinning machines which throw an oil spray. It can be prevented by wearing oilproof aprons.

Aniline cancer. Workers in factories making synthetic dyes and exposed to benzidine, α-naphthylamine, and β-naphthylamine, have a high rate of papillomata and carcinoma of the bladder.

X-rays. X-ray technicians and tube makers have a comparatively high rate of occupational cancer.

Radium. Radiologists, workers with radium, have a high incidence of occupational cancer. Radium dial painters have developed malignant bone tumors from the ingestion or inhalation of radium. Cancer of the lungs is prevalent among miners of radium ore.

Actinic rays. Outdoor workers such as fishermen, sailors, soldiers, and farmers have a high incidence of skin cancers.

Trauma. Malignant tumors may develop at the site of chemical burns and repeated traumatism. That a single trauma can cause cancer is debatable and is difficult if not impossible to prove. In order to prove it, it must be shown that the part was normal before the trauma; that the trauma was at the site of the cancer; that a sufficient interval elapsed between the trauma and the appearance of the cancer; that there was no other traumatism at the site of the cancer during this interval; and biopsy must verify the malignant nature of the growth.

Heat. Cancers can arise in cicatrices of burns, usually a number of years after the burn.

Prevention of Occupational Cancer

Workers having keratoses, warts, or xeroderma should not be employed in occupations where there is a marked cancer hazard. Processes giving off tar or pitch fumes should be enclosed. Persons working with carcinogenic coal-tar derivatives should be furnished with clean work clothes daily and be compelled to take showers after work. Protective ointments containing chemical or physical light screens are useful to protect against excessive sunlight.

IX. Methods of Investigation

In order to investigate intelligently the cause of occupational dermatoses, one must have at least a sufficient knowledge of dermatology to distinguish contact dermatitis from such ordinary nonoccupational skin diseases as psoriasis, impetigo, urticaria, pityriasis rosea, and so forth. In addition, one should have, also, a fair knowledge of the action of industrial chemicals on the skin. The actual investigations in factories will give one the knowledge of industrial processes that is another essential requirement.

Before one can hope for success in finding the cause of a particular outbreak of occupational dermatitis, it is necessary to have the experience and knowledge gained by studies of the skin hazards and the normal incidence of occupational dermatoses in the basic industries. Such studies not only acquaint one with the irritating properties of various chemicals, but often lead to the discovery of health hazards not previously reported. The basic industries should be selected for routine studies because they manufacture the chemicals used in all other factories, and their workmen are subject to the hazards of contact with these chemicals.

In proceeding with an investigation, the first step is to discuss with the plant superintendent the occurrence of occupational diseases, especially those of the skin, that to his knowledge had occurred in the factory; and to obtain from him a list of the raw materials used in the factory, and of the products manufactured. The next step is to consult with the plant physician, if there is one, or with the nurse or first-aid attendant, concerning the chief infections or diseases treated in the dispensary, and to obtain from them a little better conception of the incidence of skin diseases than was obtained, perhaps, from the superintendent. The medical records, if any have been kept, are then examined regarding the number of cases of skin lesions treated, the causes given for their occurrence, and the departments in which the patients worked. This procedure often yields a clue as to what part of the factory has the greatest skin hazards. It is also well at this time to request that those of the workers who have had occupational skin diseases or who are known to be affected at the time be called into the dispensary to be questioned and examined. This makes it possible to check and evaluate the criteria used by the plant physician in making a diagnosis of occupational dermatitis.

The superintendent is then asked to appoint someone familiar with all the industrial processes in the factory to escort the investigator through the plant. He may begin at the point where the raw materials come in and follow them through the plant until the finished product is ready for shipment. In each department visited, first interview the foreman, asking him if he knows of any workers who have now or ever have had skin diseases, and what in his opinion caused these diseases. Then go through the department and have the manufacturing process explained. Examine the hands and faces of the workers for skin lesions, at the same time taking note of their work clothes, whether they are clean or dirty, and whether protective clothing in the form of gloves, aprons, boots, respirators, and so forth is worn; note the clean-

liness of the workroom, and whether there are any safeguards on the apparatus, such as ventilating hoods; and ask each worker if he now has or ever has had any skin diseases. The names of workers who are found to be affected with skin lesions or who state that they have been affected at some time or other are taken, and at the end of the day's inspection these workers are summoned to the dispensary and examined further.

The primary inspection of the men at work takes but a short time—not over a half minute for each man. The same procedure is followed in every department, and notes concerning the industrial processes and hazards are taken. At the end of the day's inspection, usually an hour or so before the end of the day's shift, go to the first-aid room and send for the workers found during the inspection to be affected with skin diseases. Such workers are examined one at a time with only the plant physician, nurse, or first-aid attendant present. The worker is required to disrobe completely and his body is examined for the presence of skin diseases. It is important to strip the patient because often an important clue to the diagnosis is revealed that might otherwise be missed.

A card record is made of the patient, including the name, sex, age, color, and a detailed description of the worker's occupation and the chemicals with which he comes in contact. The date of entering his present occupation is noted, as is also a history of his previous occupations. A record is made of previous skin diseases and of any allergic history; a detailed account of the present skin diseases is taken, with the date of onset and the symptoms noted down; a written description of skin lesions and their location is made on the card; the patch tests, if any are performed, are also described, the names of the chemicals applied as patches, the length of time they are allowed to remain on the skin, and the resultant reactions being given. Based on this data the diagnosis is made and the actual skin irritant, if found, is named. Under the heading "Remarks" complicating skin lesions and treatments are recorded.

When a number of factories manufacturing the same products have been examined, a fair idea of skin hazards in that particular industry is obtained. The knowledge and experience gained by routine studies of industrial processes and skin hazards in basic industries prepares one to undertake intelligently the investigation of the causes of outbreaks of occupational dermatoses. The requests for such investigations come from insurance companies, the management of factories, and labor unions. Such outbreaks of occupational dermatoses usually occur when new chemicals are introduced, or when new manufacturing processes are being installed, or when there is some change made in old manufacturing processes.

While outbreaks of occupational dermatoses usually occur in only one department of a factory, it is necessary to study not only that one department, but the whole process of manufacture. Sickness records of the plant for at least a year previous to the outbreak should be studied in order to determine whether the outbreak occurred suddenly, or whether there was a gradual increase in the number of cases of dermatitis; and whether there was any connection between a sudden in-

crease in the incidence and the use of new chemicals, new processes, or changes in old processes in the factory. Detailed inquiries should be made of the superintendent, the foreman, and the workers as to changes in manufacturing processes and the introduction of new chemicals preceding the outbreak of dermatitis.

Patch tests should be performed with all the allergenic materials handled by the affected workers, in an effort to track down the offending substance. In some instances the management purchases, under trade names from other concerns, the chemicals used, and does not know their composition. It is necessary in these cases to trace the chemicals to their original source of manufacture and determine what they really are.

X. Skin Hazards According to Types of Workers or Occupations

Abattoir workers and butchers may contract anthrax and erysipeloid from infected animals. Those employed to clean intestines sometimes suffer from "hog itch," a dermatitis of the hands and forearms caused by allergy to the secretions of round worms in the hog's intestines. Glanders and actinomycosis are rare, but may occur. Butcher's pemphigus is also a rarity. Verruca necrogenica is not uncommon. Butchers and abattoir workers should immediately disinfect all abrasions and cuts. They should not scratch any part of the body without disinfecting the hands. Those engaged in cleaning entrails should wear long rubber gauntlets.

Agricultural workers may develop skin cancers from excessive exposure to sunlight. They may contract dermatitis from poisonous plants. Parasites of grain and straw may attack the skin. Ground itch (hookworm) may be contracted if shoes are not worn. Cowpox, sheep pox (ovinia), and sheep thrush may be contracted from infected animals. Agricultural workers should protect themselves against excessive sunlight. They should immediately disinfect all abrasions and cuts and wear gloves when likely to be exposed to poisonous plants.

Airplane workers may develop dermatitis from (*1*) protective coatings on duralumin, (*2*) solvents in "dopes" and paints, (*3*) cutting oils, (*4*) woods, such as mahogany, (*5*) glues, (*6*) strong caustic cleansers, (*7*) electroplating operations. Prevention consists in protective clothing against solvents, oils, and caustics, and frequent washing to remove glues.

Asphalt and pitch workers are particularly subject to comedones, acne-like lesions, keratoses, epithelioma, melanosis, and photosensitivity. To prevent these they should have a daily change of clean work clothes, take cleansing showers after work, and use a protective ointment containing physical and chemical light screens.

Bakers and millers are subject to allergic eczemas from flour and the conditioners and bleaches contained therein. Sometimes bakers develop a sensitivity to flavoring agents such as cinnamon and vanilla. The daily change to clean work clothes, and the wearing of rubber gloves are preventives.

Brick layers, cement workers, and masons are subject to dermatitis from lime, cement, and paint. Cleansing showers after work, daily changes to clean work

clothes, wearing of dustproof coveralls, protective ointments on the face, and wearing of rubber gloves are the preventive measures.

Cabinet makers and carpenters use solvents and thinners in varnishes and lacquers that are chief causes of dermatitis. The resins, both natural and synthetic, used in varnishes, lacquers, and glues, also affect some workers. Poisonous woods, such as cocobola, embuia nectandra, swietenia macrophylla, and others, may cause allergic dermatitis. Preventive measures consist of daily changes to clean work clothes, cleansing showers after work, protective ointments, and rubber gloves.

Candy makers may become sensitive to the materials used for flavoring, such as cinnamon and vanilla; they may develop dermatitis and paronychia from fruit juices and sugar. Prevention consists of personal cleanliness and wearing of rubber gloves.

Canning of fruit and vegetables. Dermatitis is fairly common among all handlers of fruit and vegetables; the juices containing sugar, acids, and essential oils and the alkalies used for cleaning and peeling may cause dermatitis and paronychia. Monilia infections of the interdigital spaces and around the nails are not infrequent. Those handling citrus fruits, peaches, tomatoes, carrots, and asparagus, are especially prone to dermatitis. Prevention consists of the wearing of rubber gloves with impervious sleeves fastened over the gloves at the wrists and impervious aprons, and personal cleanliness. Applying equal parts of lanolin and cold cream to the hands at night aids in prevention of dermatitis.

Dyeing. The strongly alkaline vat-dye liquors and the strong acid-dye liquors are more frequently the cause of dermatitis than are the dyes themselves. The mordants, especially the alkaline bichromates, often cause dermatitis. The strong scouring soaps and bleaches used on the fabrics before dyeing often cause dermatitis, as do the volatile solvents used to remove spots from the dyed fabrics. Preventive measures consist in wearing rubber gloves, impervious sleeves and aprons, and rubber boots when working on wet floors, and personal cleanliness.

Dye manufacture. Workers in this industry are exposed to strong organic and inorganic acids and alkalies as well as to intermediates, many of which are primary skin irritants and most of which are sensitizers. Most of the finished dyes are harmless but a few of them may cause dermatitis. Workers exposed to benzidine, alpha naphthylamine and beta naphthylamine may develop papilloma of the bladder. Prevention of dermatitis consists in compulsory showers after work, daily change to clean work clothes, wearing impervious sleeves, aprons, and gloves. Exhaust hoods over dusty and fume-evolving processes, or totally enclosed manufacturing processes, are necessary.

Electroplating. The acids, alkalies, and solvents used to clean the parts before plating and the irritant vapors of bichromates, cyanides, and so forth coming from the plating tanks, are skin irritants. Prevention consists in daily change to clean work clothes, wearing rubber gloves, impervious sleeves, and aprons, petroleum jelly in the nostrils to prevent nasal mucitis, protective ointments on the face, and exhaust ventilation over plating tanks.

Explosives manufacture. Workers exposed to tetryl, TNT, picric acid, and the picrates, have the hair and hands discolored and may also develop dermatitis of the face and hands. Fulminate of mercury does not discolor the skin but does cause dermatitis. Ammonium nitrate, DNT, and Hexite also cause dermatitis, but not as frequently as tetryl and TNT. Prevention consists in daily change to clean work clothes, showers after work, wearing impervious gloves, protective ointments on the face, and, for tetryl workers, petroleum jelly in the nostrils.

Felt hat manufacture. The "carrots" used on the furs (either mercuric nitrate or the alkali carrots) are skin irritants. The "starting solutions" are also skin irritants, as are the bichromates used in dyeing the fur. The "sizings" used to stiffen the felt may cause dermatitis. Prevention consists in wearing impervious sleeves, aprons, and boots when working on wet processes.

Fertilizer manufacture. Workers are exposed to the dust of nitrates, calcium cyanamide, fluorides, and other irritant chemicals. Bone dust irritates some workers. The solvents used to extract fat from animal refuse may cause dermatitis. Prevention consists in allaying of dust, use of exhaust hoods over dusty processes, daily change to clean work clothes, and showers after work.

Furriers may develop dermatitis from the chemicals used to preserve the pelts: salt, arsenic, and lime. Those engaged in "fleshing" suffer from loss of the nails. The mordants and tanning agents, such as bichromates, alum, and formaldehyde, may injure the skin. Aniline salt, aniline black, and paraphenylenediame are the principal irritant fur dyes. Prevention consists in the wearing of rubber gloves, impervious sleeves and aprons, rubber boots, and clean work clothes.

Garage workers may develop dermatitis from gasoline and from the strong soaps used to clean cars. These soaps if used to clean the hands cause dermatitis. Folliculitis of the arms and the thighs occurs from exposure to oils and greases. Prevention consists in wearing impervious sleeves and aprons, daily change to clean work clothes, and showers after work.

Glass workers. Alkalies, such as lime and sodium carbonate, and arsenic cause dermatitis among "batch mixers." Etchers may develop dermatitis from hydrofluoric acid. Lesions of the lip and teeth occur among glass blowers. Prevention consists of daily change to clean dustproof work clothes, rubber gloves for etchers, petroleum jelly in nostrils for those exposed to alkalies and arsenic, and showers after work.

Hair dressers and beauticians may develop dermatitis from ammonium thioglycolate and alkalies used for waving or straightening hair; from resins used to keep the hair curled or straight; from alkalies and solvents used to manicure; from hair dyes, tonics and perfumes. Mycotic and pus infections may be contracted. Prevention consists in washing the hands after handling each customer, wearing clean rubber gloves and impervious sleeves and aprons, anointing the hands with equal parts of lanolin and cold cream before retiring at night.

Insecticide makers and users. All insecticides are skin irritants. Workers mak-

ing and using them should protect the skin by showers after work and impervious clothing changed daily.

Iron and steel workers. Those engaged in front of furnaces suffer from heat rashes and telangiectases. Those mixing batches may get dermatitis from lime and chromium. The acids and alkalies used in "pickling" may cause dermatitis as do "drawing" compounds used in drawing wire. Nitrate, cyanide, and soda ash may cause dermatitis among "case hardeners." Lubricants, quenching and cutting oils may cause folliculitis and acne. Core and mold makers may develop dermatitis from the chemicals used in the sand. Prevention consists in showers after work, daily change to clean work clothes; canvas or leather gloves to handle steel or wire; rubber gloves for "picklers."

Laundry workers. Principal skin hazards are disinfectants, strong alkalies, soaps, bleaches, and solvents. Dermatitis may be contracted from irritant chemicals on soiled clothes. Prevention consists in wearing rubber gloves, impervious sleeves, and aprons, and in rubbing equal parts of lanolin and cold cream into the hands before retiring at night.

Leather tanners. Those engaged in handling the fresh hides are subject to the action of lime into which the hides are immersed as well as to the preservatives used to preserve the hides. The chemicals used for removing the hair are lime, and arsenic and sodium sulfides. All of these can cause ulcers and dermatitis. The tanning agents both vegetable and chemical such as sumac, bichromates, and synthetic tannins may cause dermatitis. The dyes used on leather affect the skin of some workers. Anthrax may be contracted from infected hides. Prevention consists in showers after work, wearing impervious gloves, sleeves, and aprons, daily change to clean work clothes, and immediate disinfection of all cuts and abrasions.

Machinists. The chief skin hazard is from the cutting oils, especially the insoluble cutting oils. They cause folliculitis, acne, and pustules, and sometimes allergic eczemas. Metal chips may wound the skin. The solvents used for degreasing are also a prolific source of dermatitis. Alkaline coolants may defat the skin and cause dermatitis. Prevention consists in showers after work, daily change to clean work clothes, wearing impervious sleeves and aprons, protective ointment.

Painters. Most of the dermatitis among painters is caused by solvents and paint thinners and not by pigments and dyes used in the paint although some persons may be allergic to these chemicals. Paint removers are all strong skin irritants, as are the wood preservatives such as arsenic, tar distillates, zinc chloride, and bichromates. Prevention consists in showers after work, daily change to clean clothing, impervious sleeves, aprons, and gloves.

Paper makers. The alkalies used in digesting wood pulp, the black and green liquors, the bleaching solutions, and the resins used for sizings are the principal skin irritants in paper manufacture. Prevention consists in personal cleanliness and impervious sleeves, gloves, aprons, and boots.

Petroleum field workers and refiners. Workers in the oil fields, especially

pumpers, pipe pullers, and repairmen, are subject to folliculitis, acne, and keratotic lesions produced by crude petroleum. In torrid climates they are also subject to the keratoses and melanoses produced by the combination of the oil and actinic rays. The harsh cleansers used to remove oil and grease from the skin also may produce dermatitis.

In refineries the same hazards are present and in addition the crude paraffin waxes may cause acne, boils, and keratoses. Prevention consists in cleansing showers after work, daily change to clean work clothes, and the use of mild cleansers. Workers exposed to actinic rays should use ointments containing light screens.

Photoengravers and lithographers. The chief skin irritants are the alkaline bichromates used on the plates, the acids used in etching, and the photo developers. Solvents used for cleaning plates may cause dermatitis. Prevention consists in wearing long rubber gloves and imprevious aprons when handling the irritant chemicals,

Photographers. The principal irritants are metol, used for photo developing, and bichromates used for blueprint developing; pyrogallol, hydroquinone, silver. sulfides, platinum, and mercury salts may also cause dermatitis. Prevention consists in wearing long rubber gloves and impervious aprons when working in the developing and fixing solutions.

Plywood workers. The principal skin hazards are the glues, especially those made of synthetic resins and those containing strong alkalies, such as the casein glues. Some workers may become sensitized to the woods. Personal cleanliness, daily change to clean work clothes, protective ointments on the face, and the wearing of washable light leather gloves are methods of prevention.

Printers. Solvents used to clean the presses are the principal skin irritants. Harsh soaps to remove dye from the skin also cause considerable dermatitis. Some persons may be allergic to dyes. Prevention consists in wearing rubber gloves, impervious sleeves, and aprons when cleaning presses, and using mild soaps and cleansers to remove inks from the hands.

Rayon manufacture. Workers in contact with wood pulp treated with sodium hydroxide may develop dermatitis and ulcers. Those exposed to carbon bisulfide may develop dermatitis and systemic poisoning. Workers at the precipitating baths are exposed to alkali viscose coming from the spinnerettes as well as to sulfuric acid in the baths. The bleaches used on the rayon are skin irritants. The preserving solutions in which cellulose caps are immersed for storage are skin irritants. Workers spinning and coning rayon thread may develop allergic dermatitis from the ingredients in the coning oils. Makers of acetate rayon are exposed to acetic acid and acetone and those making cellulose nitrate are exposed to nitric and sulfuric acids as well as solvents. Prevention consists in wearing rubber gloves, impervious sleeves, and aprons, and daily change to clean work clothes.

Resin manufacture. Workers exposed to phenols, aldehydes, urea, the monomers of polymerized resins may develop dermatitis from these chemicals. Hexamethylenetetramine used in some of these resins also causes dermatitis. Prevention

consists in daily change to clean work clothes, showers after work, impervious sleeves, aprons, and gloves, and protective ointment on the face where dust and fumes cannot be exhausted.

Restaurant workers. Soaps and other alkali cleansers cause dermatitis among dishwashers. Mycotic infection of the nails is an occupational disease of dishwashers and soda-fountain attendants. Fruit and vegetable juices may cause dermatitis. Prevention consists in wearing rubber gloves, impervious sleeves, and aprons, the use of mild cleansers for the skin, and applying lanolin to the hands before retiring.

Road makers. Workers are exposed to the action of actinic rays, tar, and asphalt, which may cause melanosis, cancer, photosensitivity, acne, and folliculitis. Prevention consists in showers after work, daily change to clean work clothes, and protection against the sun.

Rubber manufacture. The chief irritants are the accelerators, antioxidants, and other chemicals going into the manufacture of rubber, the sulfur chloride used for "vapor curing," and solvents used to make rubber cements. In reclaiming rubber, alkalies are the chief skin irritants. In the manufacture of synthetic rubber, dermatitis may occur not only from the above-named chemicals, but also from styrene acrylonitrile, and other chemicals used. Prevention consists in showers after work, clean dustproof work clothes daily, and protective ointments on the face to protect from dusts and fumes.

Ship builders. Welders are subject to flash burns (see *welders*) and electricians handling cables are subject to acne (see *wax makers*).

Solderers. Hydrochloric acid fumes and zinc chloride may cause dermatitis. Prevention consists in wearing impervious sleeves and applying protective ointment to the face.

Sugar refiners. Hot solutions of sugar crystallize on the skin and enmesh the hairs; boils may result when crystals are pulled off and hairs are pulled out. Paronychia may occur, and also dermatitis from alkalies used to purify sugar and from the dehydrating action of sugar. Prevention consists in daily change to clean work clothes, impervious sleeves, gloves to handle dry sugar.

Varnishers and lacquerers. The resins are skin irritants as are the solvents and thinners; the dyes and pigments are only rarely so. Prevention consists in daily change to clean work clothes, rubber gloves, and impervious sleeves.

Wax makers (synthetic). Solid chlorinated hydrocarbons cause acne-like lesions. Prevention consists in showers after work, daily change to clean work clothes, and proper exhaust ventilation.

Welders and helpers. Flash burns may cause dermatitis, melanosis, and "eye flash." Dermatitis occurs from fumes of irritant metals contained in alloy steels. There is danger of spark burns. Prevention consists in wearing proper masks and dark glasses, and flameproof clothing.

Chapter Twelve

The Visible Marks of Occupation and Occupational Diseases*

CAREY P. McCORD, M.D.

Introduction

Some, but not all, trades lead to external markings or signs on workers that may serve to identify either the trade or the diseases associated with the trade. In times past the term "stigmata" has been widely applied to these marks, but this term is at times inappropriate and confusing. In medicine, "stigma" or "stigmata" has been chiefly limited to the skin, and often possesses religious connotation. In general, the term denotes disgrace or inferiority. This is far removed from the purposes of a manifest of the signs of various trades imprinted upon the worker, many of which constitute honorable badges of long years of service. For this reason the designation "stigmata" is carefully avoided in relation to occupation. As here presented, the markings of trades and trade diseases are limited to those evidences that may be seen by the layman as he may observe attired human beings, at the factory entryway, on a streetcar, or as the observer passes along the aisleways of a work department. The term "layman" in this instance merely indicates that the observer is neither a physician, nurse, nor dentist. Conversely, the observer might be highly skilled as an engineer, a chemist, or lawyer. Frequently the signs that may be observed are not single but occur in groups to which the term "syndrome" is well applied. Thus, given a known exposure to manganese, anyone presenting an expressionless, masklike face, who is unable to purse the lips as in whistling, whose gait is apparently not quite controlled, and who indulges in fits of unprovoked laughter or crying, should be suspected as having manganese poisoning. These signs constitute the syndrome of that disease.

While some definite medical ends may be served by a knowledge of occupational signs in their hundreds of variations, greater interest may reside in intellectual curiosity about the tell-tale indications of different trades or different trade diseases as branded onto the bodies of those who ply them. On a streetcar or anywhere else,

* From the Industrial Health Conservancy Laboratories, Detroit, Michigan.

there might be observed a man who reveals a circular hole about the size of a dime in the midline of his teeth as they rest in apposition. Further, it might be noted that this individual is having some difficulty with his breathing, the inhalations being feeble and short while the exhalations are prolonged and possibly labored. The astute observer at once will realize that he is in the presence of an old-time glass blower with emphysema—the characteristic occupational disease of that trade. The unfavorable critic may urge that such is not the case, that the observed individual is merely an aged pipe smoker with asthma. But there is a difference. The pipe smoker's dental hole is smaller, more likely to be oval and, moreover, to be right or left of the midline. Other signs may reveal not especially the trade, but a specific occupational affection. Let it be assumed that a stranger unexpectedly enters a workroom, whereupon the workers therein immediately appear to be frozen in whatever position exists at the moment. An entire group of workers on such an occasion may resemble a grotesque lot of statues—utterly embarrassed, incapable of motion, little capable of speech. To the knowing one, these signs at once should suggest the erethismus of mercury poisoning. One of the classical stories about mercurial erethismus centers about a group of hat makers with nondisabling mercury poisoning who were gathered together after work in a saloon for drinking purposes when a stranger entered. During the entire time the unfamiliar person remained, not one of these hat makers was able to lift a glass to his lips or to make other movements—because of pathologic shyness and timidity.

There is no intention here to suggest that all occupational diseases present obvious outward evidences of their existence so that he who runs through a factory may make precise diagnoses. More often than not, when a disease state has reached the point of gross, external characteristics, the time has long passed at which the condition should have been recognized. It is equally obvious that many visible marks are related to nonoccupational diseases and injuries. It is nonetheless true for nonmedical workers in industry, and significantly for the industrial hygienist, the safety engineer, the chemist, the foreman, the superintendent, that a wide acquaintance with unusual markings on the body or in the actions of workers may serve an end helpful to all. Such workers should know that many drugs taken internally may lead to peculiar markings on the skin; thus, some laxatives containing phenolphthalein may, even when taken by the manufacturer's directions, produce pigmented skin blotches as large as those of the leopard. They should know that some diseases and some work materials may identify themselves in the breath of the person involved, even though this does not constitute a visible sign. They should know that some tradesmen may suggest their jobs through bodily markings or actions, for example, the dirt farmer by his bronzed, warty skin, the train dispatcher by his proneness to cock his right ear toward you because of partial deafness in the left. They should know that the evidences of some acute diseases may be found in the altered color of the skin, as the cherry red skin of the victim of carbon monoxide. They should know that from the gait of some workers some diseases may be spotted

with precision, as in the case of some syphilitics who go about their duties with high, slapping steps like a prancing horse.

The unfavorable critic, with some justification, may claim that a mere familiarity with a large number of heterogeneous signs provides insufficient information for any practical application—that engineers, hygienists, chemists, and others may not be transformed into other than pseudo-physicians by the acquisition of miscellaneous lore about the external characteristics of diseases. Conceding part of the point, there still remain opportunities for the simple application of facts gained, as in the following instance.

Expansion in a small plant led to the employment of a number of young women for the first time and under somewhat unfavorable work conditions. Soon thereafter, more than half of the women developed what was for them an alarming livid eruption over their shins, roughly resembling a bluish-red Scotch plaid. No male worker, although in the same department, was afflicted. Sheer panic was in the making, claims and acrimony. Then came the safety engineer, not a physician, but experienced in the markings of some diseases. He simply pointed out that in that expanding department it had been necessary to introduce several coal stoves, and that the girls, being more thinly clad than the men, had stood or sat for long periods close to these hot stoves, with the resulting patchy lattice work corresponding to the distribution of the superficial blood vessels in these girls' lower legs. This common condition is known to the dermatologist as "erythema ab igne"—"skin redness from fire." This condition is familiar to every country boy and girl who goes barefoot late in the fall or early in the spring and hovers close by the open fireplace or stove. It is information of this character that provides ever-expanding opportunities for nonmedical personnel in industry.

Widely, characters in fact and fiction have become famous through infinite capacity to observe and interpret apparently trivial external markings on the human body. In no small part, the fame of Osler, America's greatest contribution to medicine, rests upon this ability, while in fiction Sherlock Holmes, as created by another physician, gained part of his immortality through this same quality of genius. However, there is nothing so sacred in the domain of medicine as to bar nonmedical personnel in industry from observing physical peculiarities of workers, and setting in motion appropriate steps that may lead to helpful interpretation.

Stigmata of Degeneration

In an earlier period, and chiefly among criminologists, a vogue long existed centering about numerous anatomic or physiologic deviations from the usual in relation to criminals, perverts, the insane, the epileptic, the feeble-minded, and the degenerate. These deviations were termed "stigmata of degeneration," and this term designedly indicated inferiority or disgrace. It was thought that the unfortunate possessors of such abnormalities as supernumerary fingers, webbed toes, pointed ears, or microcephalic (small) heads might in the over-all picture be more frequently encountered in the undesirable citizenry than elsewhere. While in feeble-

minded, insane, or penal institutions there may be found greater numbers of divers stigmata of degeneration, it does not follow in every instance that these markings are significant. In a court trial, some stigmata of degeneration might as often be found on the prosecuting attorney, the judge, the doctor in the witness chair, as on the prisoner at the bar. Inevitably, many of these stigmata of degeneration will be exhibited by industrial workers and be wholly unrelated to occupational signs. Since so many unhappy interpretations of these congenital or hereditary markings are made, it may be desirable, even on a negative basis or basis of sympathetic understanding, that some of these so-called degenerative signs here be included.

The most obvious stigmata of degeneration are anatomic. On a lower level of discernibility are physiologic and psychic signs. On an anatomic basis, almost any organ, system, or portion of the body may be involved, or even the body as a whole. Thus, there may be decidedly large, small, elongated, or asymmetric heads. Common are deformities of the palate, best observed as "harelip." Quite apart from dental anomalies associated with work causes, there may arise congenital dental defects. Tongues may be excessively large, small, or bound down. In the eyes at birth there may exist cataracts; the two eyes may be of wholly different color; the eyes may be crossed (strabismus). Occasionally, eyes may be pathologically small. Unusual closeness of the eyes one to another is sometimes regarded as a sign of degeneration. A number of stigmata are associated with the ears, and perhaps without great significance, such as: the implantation of ears at different levels, excessive length of ears, the absence of one or both ears, very small ears, the binding down of the lobule to the neck, the congenitally thickened or knobbed ear, which is in distinction to the "cauliflower ear" of the boxer, ears that are implanted too far forward or too far rearward, the ear without external auditory canal, etc.

In the realm of stigmata of limbs, there may be mentioned: excessive numbers of fingers or toes, varying degrees of webbing of fingers or toes, the absence of one or more fingers or toes, improper location of fingers or toes, excessive length or shortness of entire limbs or portion of limbs, such as in achondroplasia (one form of dwarfism). In addition, many stigmata are seen in such instances as the clubfoot, entire absence of certain muscles or muscle groups, or the absence of certain joints.

A wide variety of congenital peculiarities of the skin may be classed in the category of degeneration. A few of these are the absence or scantiness of hair, the occurrence of hair in unusual places, unusual colors of the skin, albinism, absence of nails, ichthyosis (fish scale skin), congenital tumors, and so on.

Some deviations from the normal affect the body as a whole, such as: dwarfism, gigantism, infantilism, femininism, masculinism, certain types of obesity, progeria (childhood characterized by premature senility), mongolism (one form of physical and mental defection characterized by physical resemblance to Mongol races), and so forth.

In like manner, anatomic stigmata of degeneration by the hundreds have been associated with every other portion of the body including the lips, nose, neck, chest, spinal column, glands, etc. In order that these anatomic defects may not appear

too far afield from the practical, let it be pointed out that with few exceptions all inguinal hernias represent congenital defects, constituting in the majority of instances failure of complete anatomic structure in the inguinal area. Further, lest there be prideful feeling of freedom from the stigma of defects, let it be pointed out that every woman or man whose beauty or handsomeness partly depends upon winsome or seductive dimples is merely presenting minor anatomic defects. All persons possess some anatomic defects, and only when the number is large or the condition profound should much significance be attached to them as evincing degeneration. It is not remarkable that the mythologies of primitive people should center about some of the severer malformations of bodies. Thus, Janus undoubtedly had his counterpart in some actual human born with two faces. Medusa probably is to be associated with some actual woman afflicted with numerous horny growths of the scalp. The legendary mermaid finds basis in those rare cases of sympus or sirenomelus, a gross malformation in which the two lower extremities are fused. In more modern times and reminiscent of the side show, gross stigmata of degeneration are exhibited as the "turtle boy," the "dog-faced woman," the "bearded lady," and so forth.

The stigmata of degeneration on a physiologic basis are not so numerous, or at least not so obvious, although many compel attention. Likewise, physiologic deficiencies on a hereditary or congenital basis are not so readily separated as the anatomic ones from those caused during postnatal life. Again it may be pointed out that physiologic stigmata of degeneration may involve any portion of the body. Representative examples are: color blindness, some deafness, mutism, stuttering, blindness, constricted visual field, migraine, anesthesia, hyperesthesia, astigmatism, epilepsy, endocrine dysfunction (abnormal function), colored sweat, hyperodorous sweat, vicarious menstruation, dysfunction of appetite, delayed puberty, etc. Many instances of such conditions as deafness and blindness in no sense represent stigmata of degeneration.

In the psychic province there are unfortunately almost unlimited evidences of degeneration. These embrace some, but not all, feeble-mindedness, idiocy, imbecility, insanity, precocity, eccentricities, sexual perversions, and so on. Even genius itself, when warped, may be a sign more of degeneration than of exceptional brilliance.

The practical man at this point may be disposed to disavow any connection between the foregoing and the day-by-day world of medicine and industrial hygiene. This attitude is unwarranted. Many hundreds of thousands of workers go about their tasks with continuous mental, if not physical, discomfiture as a consequence of the departure from the usual found in their bodies, their physiologic functions, or their minds. They are in need of human understanding, of medical guidance. After all, industrial medicine is not limited to lead poisoning, silicosis, and broken bones.

Marks from Work and Work Diseases

Manifestly, occupational markings on the body are not the stigmata of degeneration in the sense previously used in this presentation. Almost equally manifest

is the fact that work signs are directly acquired and are not congenital. This statement is not precisely true since some occupational affections of one or both parents may illy influence the offspring. Hence, some children may present stigmata of degeneration when one or the other of the parents has suffered from such afflictions as lead, radium, or phosphorus poisoning. These and other materials constitute race poisoning and may, in fact, contribute to the degeneration of offspring.

As under foregoing circumstances, work marks, as observed in those portions of the body of an attired person that may be seen with the eye, may involve any external portion of the body, as: the skin and its appendages, the eyes, ears, nose, teeth, lips, limbs, and bones. Other signs may derive from posture, gait, mannerisms, or facial expressions. A number of more common ones such as should challenge the attention of nonmedical persons are listed on pages 387–408. For the purpose of differentiation between occupational and nonoccupational afflictions, some nonoccupational affection signs are included. R. M. I. represents "recommend medical investigation."

Summary

In cursory fashion, numerous signs of disease and near-disease states directly or indirectly related to work are presented in terms designed for nonmedical personnel.[1] The purpose has been twofold: (*1*) the hope of piquing the interest of nonmedical personnel in medical matters, and (*2*) the hope of bringing to the attention of physicians larger numbers of persons at workplaces genuinely in need of medical care.

[1] For more extensive and technical medical data, reference is made to: W. E. and H. F. Robertson, *Diagnostic Signs, Reflexes and Syndromes,* 2nd rev. ed., Davis, Philadelphia, 1942. W. M. Barton and W. M. Yater, *Symptom Diagnosis,* 4th ed., Appleton-Century, New York, 1942. F. Ronchese, *Occupational Marks and Other Physical Signs,* Grune and Stratton, New York, 1948.

Common External Marks of Occupation or Occupational Diseases or Other Diseases

Mark or sign	Probable cause	Significance	Comment
		Skin	
Pallor—transient (white skin).	Temporary blanching from fainting, fear, pain, nausea, loss of blood, shock.	Dependent on cause.	Not necessarily occupational.
Pallor—persistent (white skin).	Anemia from any of many causes.	R. M. I.	Many specific types of anemia related to work, such as "baker's anemia."
Pallor—localized (white skin).	Hysteria, freezing, pressure, localized poisoning such as from insect stings.	R. M. I.	More common among women.
Abnormal color (cherry red skin).	Carbon monoxide.	May be absent in carbon monoxide poisoning. More likely to involve ears, cheeks, lips, fingertips; instead of cherry red, carbon monoxide color may be yellowish red, greenish red, bluish red. R. M. I.	Patient usually prostrate.
Abnormal color (slatish purple skin).	Silver.	Condition of argyria; may be uniform, may be patchy. Color not always same in different cases.	Not always occupational; must have been exposed to silver; essentially incurable; not disabling.
Abnormal color (slatish violet, red splotches on skin).	Phenolphthalein.	Skin damage from laxatives containing phenolphthalein; splotches usually on arms and chest; may be one or a score; variable sizes; persistent; no superficial skin rash.	Sometimes leads to compensation claims. Unwarranted except in phenolphthalein workers.
Abnormal color (bluish purple skin).	Methemoglobinemia.	Distribution may be limited to ears, lips, fingertips, or possibly generalized. R. M. I.	May be associated with other forms of abnormal hemoglobin, such as sulfhemoglobin.
Abnormal color (bluish purple). Cyanosis.	Heart disease.	Resembles preceding item as to color, but not cause; common manifestation of cardiovascular disease. R. M. I.	Ordinarily not occupational.

(continued)

Common External Marks of Occupation or Occupational Diseases or Other Diseases (*continued*)

Mark or sign	Probable cause	Significance	Comment
	Skin, *continued*		
Abnormal color (yellow jaundice icterus).	Bile in skin; many causes of jaundice, including occupational causes, catarrh, cancer.	Depends upon exact cause, such as carbon tetrachloride and trichloroethylene. R. M. I.	In the young, commonly catarrhal; in the middle aged, usually gall bladder disease; in in the old, usually cancer.
Abnormal color (bronze).	Many causes, such as suprarenal disease, arsenic, pellagra.	May be universal, diffused, or localized. R. M. I.	Important if extensive and persistent.
Abnormal color (coffee color).	Endocarditis.	May resemble Addison's disease or nicotinic acid deficiency except for distribution of latter. R. M. I.	Unrelated to work as cause.
Abnormal color (yellow). Carotinoid.	From the eating of excessive quantities of carrots, squash, oranges.	Harmless; rapidly disappears on correcting diet; resembles jaundice.	Most often found on palms and soles and around nose; unlike jaundice, does not involve eyes.
Abnormal color (yellow). Picric acid.	Picric acid and picrates.	Usually limited to point of contact.	May be associated with dermatitis; some picrates used in the treatment of burns may both discolor skin and induce dermatitis.
Abnormal color (orange). Tetryl.	Munition materials.	Discolored area limited to contact points; may be associated with dermatitis.	Sometimes removed by washing.
Abnormal color (green).	Either from sweat from copper content, or external contact with fine copper.	Clinically not important; at times may be washed away.	Hair may turn either green or blue; disturbing to workers, particularly women.
Abnormal color (bluish-green streak or blotches).	Powder burns or ground-in coal dust; usually limited to miners, and chiefly coal miners.	Not ordinarily disabling, although previous injury may have been disabling.	May resemble chlorosis in appearance.
Abnormal color (hectic flushed cheeks).	Heart disease or tuberculosis.	Represents localized capillary dilatation.	In tuberculosis occurs only in far advanced state. More discernible in men.
Abnormal color (red skin).	Impending sunstroke, high blood pressure; may be natural for some types or races.	R. M. I.	May indicate fever; may be localized as on head, cheeks, or hands.
Abnormal color (leucoderma).	May be caused by external contact with certain rubber antioxidants. Monobenzyl ether of hydroquinone.	Frequently from nonoccupational causes; vitiligo; may be related to avitaminoses.	More prominent in Negroes and other dark races; loss of pigment fairly readily spontaneously replaced in some conditions.

Abnormal color (absence of normal skin sheen in Negro)	May be caused by any organic disease.	In reflected light, normal skin sheen almost invariably present in absence of organic disease.	A possible test for malingering in the Negro.
Abnormal color (excess pigmentation).	May be due solely to sunburn; some industrial causes, including superficial infection; nicotinic acid deficiency.	May be localized, spotty, or generalized; growing pigmented moles dangerous. R. M. I.	All marked hyperpigmentation without obvious cause should be investigated; characteristic of many trades, such as sailors. Bismuth, mercury, and arsenic used for therapy may induce excess pigmentation; also some cologne waters.
Abnormal color (any color—industrial tattooing).	Mechanical imbedding of fine industrial materials; any color.	Usually limited to small areas. Equivalent of tattooing; not disabling.	Frequently associated with some scarring.
Abnormal color (any color).	Scores of chemicals directly color the skin, such as silver nitrate.	External contact with many types of work. Materials discolor skin with or without producing dermatitis, such as materials of photographers.	Such skin coloration frequently only identifies the trade, but may be associated with dermatitis.
Rashes (misc.). Dermatitis.	Almost unlimited industrial causes; bacterial and fungal infections; drugs used for therapeutic purposes; mechanical and physical factors involving any portion of the body.	Types, sites. severity, diagnostic features too numerous to receive mention. Significance depends on exact cause and severity. R. M. I.	Apart from mild acne, mild seborrhea, mild erythema, mild sunburn, all skin rashes should be investigated. See subsequent references to distribution patterns of dermatoses.
Scars.	Obviously many; mechanical, chemical, infection.	Often serves as proof of previous disease states, such as chicken pox, smallpox, syphilis, "commemorative scars," i.e., smallpox vaccination; or identifies trades such as moulders from multiple burn scars on lower legs.	Scars suggest, when on thumb, shoemakers and skivers; on tongue, epileptics; when jagged on nose and face, windshield accidents; when short and straight above collar-bone, tuberculosis; when long and curved across neck, thyroid operation; long, linear scars, knife wounds; when jagged and furrowed, from gun shot accident; behind ears, mastoid disease; irregular, oblique on neck, scrofula; star-shaped at base of neck, previous tracheotomy; multiple burn scars on forearm, welders; pitted scars on back, shoulders and face, healed acne; pitted scars on forehead and face, chicken pox or smallpox.

(continued)

Common External Marks of Occupation or Occupational Diseases or Other Diseases (*continued*)

Mark or sign	Probable cause	Significance	Comment
	Skin, *continued*		
Skin parasitism (scabies, pediculosis).	Animal parasites.	May be chiefly indicated by scratch marks. Lice or nits may be seen on hair. R. M. I.	Readily eliminated from intelligent persons; recurrences probable in unintelligent, unhygienic persons.
Skin atrophy.	May indicate normal senility or may constitute portion of damage from dermatoses; from many industrial causes.	Typical example—long standing x-ray dermatitis.	Some atrophy irreparable; further exposure elimination always desirable.
Capillary dilatations (chronic).	Many causes both industrial and nonindustrial, such as alcoholism and x-ray exposures.	Minor condition of obscure cause and significance; cosmetically unattractive.	If limited, sometimes may be removed by electrolysis.
Keloids.	Peculiar skin hypertrophy following superficial injury.	More common among Negroes; usually follows mechanical injury, such as incised wound; characterized by overgrowth of scar tissue at site of previous injury; tumorlike; multiple or single.	Occasional troublesome sequela of industrial injury.
Itching (pruritus).	Numerous; both industrial and nonindustrial.	Obviously not a visible mark. Scratch lines constitute the mark. May be associated with neurosis, dermatitis, parasitism, diabetes, leukemias. R. M. I.	Undue scratching of head suggests seborrhea or lice; scratching on back of shoulders, usually acne; scratching of feet, frequently fungal dermatitis; scratching in older persons, frequent in diabetics; scratching of anal region, parasites, fungal dermatitis, or neurosis.
Anesthesia, hyperesthesia, paresthesia.	Usually neuroses and unassociated with work; also chemicals, such as formaldehyde, phenol.	Not visible markings; encountered from complaints of increased localized skin sensitivity; numbness, burning, pricking; may be symptom in some occupational disease, such as arsenic poisoning. R. M. I.	More common among pharmaceutical workers, lepers, pneumatic tool operators.
Hair abnormalities (patchy baldness—alopecia areata).	Common causes—syphilis, arsenic, fungal infections; thallium, barium sulfides; synthetic rubber intermediates.	Industrially more important than widespread loss of hair because of possible industrial causation. R. M. I.	Some forms of patchy baldness may involve eyebrows, beard, eyelashes, and the cause may be unknown.

Hair abnormalities (alopecia totalis).	Baldness in industry; may be caused by x-ray, industrial or medical.	Extensive baldness commonly unrelated to work causes, and perhaps more related to testicular function, heredity.	Any sudden extensive baldness or any baldness occurring in groups of workers quickly should be investigated.
Hair abnormalities (blue or violet colored hair).	Suspect improper or excessive hair dyeing; sometimes deliberate.	Usually unrelated to work, but various work materials settling on hair or scalp may impart divers colors.	Not disabling and usually temporary.
Loss of nails.	Both industrial and nonindustrial causes, such as arsenic, fungal infection, alkalies.	Depends upon specific cause. R. M. I.	Frequently nails are slowly separated from bed among dishwashers, bottle washers, laundry workers. etc.
Discoloration of nails.	Many industrial chemicals.	Many different colors produced, such as purple from acetanilid, brown from chromates, yellow from TNT, yellow from nitric acid, black from mercury, brown from photographers' chemicals, light yellow from picric acid, brown from hair dyes; many others.	Apart from contact, some nail discoloration may be produced as part of general involvement as in argyria.
Nail inflammation (and tissues immediately around nails).	Large number of industrial and nonindustrial chemicals; also nonindustrial infection.	Among many others, it occurs among confectionery workers, arsenic workers, bakers, bricklayers, chemists, dye workers; seek out particular exposure.	Nails themselves little subject to inflammation. See Chapter Eleven.
Nail dissolution.	Many industrial keratin solvents; notably alkalies.	Complete destruction of nails rare; typical examples of causes —formalin, cement.	Outstanding feature inflammation of tissues adjacent to nails.
Nail deformities (thickening, curvature, pitting, linear markings, spotting).	Large numbers of industrial contact chemicals.	Common among furriers, dyers, lace makers, packers, cordage makers, thallium workers, auto washers, engravers, etchers, glass makers, miners, sulfide workers, x-ray technicians, string instrument players, tanners, many others.	Apart from infection, condition rarely disabling. White spots and transverse markings may indicate antecedent disease.
Vagabond's skin.	Lice.	Deep, patchy bronzing of skin from irritation of lice bite and possibly lice excreta.	Usually associated with low order of personal hygiene.
Morphea.	Unknown.	Diffused white spots, usually over torso and upper extremities representing a patchy scleroderma.	Startling when present on Negroes or other dark races.

(continued)

Common External Marks of Occupation or Occupational Diseases or Other Diseases (*continued*)

Mark or sign	Probable cause	Significance	Comment
	Skin, *continued*		
Pathological sweating.	Many nonindustrial causes, but sometimes seen in lead poisoning.	Unusual sweating may be localized, odoriferous, colored, excessive. Sometimes found in heart disease, rickets, syphilis, palsy, tuberculosis, goiter, etc.	In arsenic or lead poisoning, abnormal sweating usually local to parts involved in neuritis.
Brick red (warm weather). Plum colored (cold weather).	Polycythemia (pathologic increase in numbers of red blood cells).	May be a manifestation of repeated exposure to carbon monoxide in relatively low concentrations. R. M. I.	Engorgement and congestion of superficial blood vessels. Most prominent on face. May involve conjunctivae.
Paroxysmal face and head flushing.	Chiefly associated with the menopause, this type chiefly limited to women 40 to 50.	May be associated with mental depression, excessive perspiration, weakness, insomnia, emotional instability.	Not occupational.
Lymphangitis.	Infection.	Red streak up arm or leg. Alarming indication of extension of localized pyogenic infection. R. M. I.	Frequently associated with "kernels" such as in axilla or groin.
Keratosis (farmer's warts).	Excessive sunlight, ultraviolet light, etc.	Represent warty, flat, or horny, persistent overgrowth of outer layers of skin. Characteristic of past middle age life; usually limited to exposed parts of skin; characteristic of many trades including farmers, sailors, fishermen, gardeners, trappers.	Rarely become cancerous; readily removed by electrocauterization, by x-ray and by electric needle; less well by keratin solvents. Quite common both in and out of industry.
Asbestos warts.	Mechanical penetration by asbestos fibers; possibly chemical action akin to production of silicotic nodules.	Condition usually limited to fingers and hands.	Similar condition with glass fiber workers, but in that case always mechanical.
Tumors (on skin).	Several types, both benign and malignant. Commonest variety, epithelioma.	Apart from nongrowing warts and obvious abscesses of skin, any enlarging mass on or in skin should be investigated. R. M. I.	Pigmented moles are prone to become malignant.
Tumors (beneath skin).	Frequently harmless, fatty tumors (lipomas). Attain to large size.	Because of uncertainty, every mass beneath the skin should be investigated by a physician.	Skin over lipomas, if squeezed, becomes dimpled, "orange peel" sign. See next item.

Subcutaneous lymph nodes (enlarged).	Lymph nodes of neck, axilla, groin, etc., may become enlarged and observable; many causes, but chiefly infection. "Kernels."	Depends upon precise cause of gland enlargement. R. M. I.	Lice in head hair frequently is cause of enlarged lymph glands on sides of neck.
Skin cysts.	Plugged-up oil glands.	Large or small sacs in skin with fluid or pasty content; few or numerous cysts may appear almost anywhere on skin surface, particularly about head; on scalp called "wens"; relatively harmless; disfiguring.	Milium "white heads" ordinarily represent multiple minute cysts.
Work callosities.	Pressure and friction.	Characteristic of many trades, the exact location usually identifying the trade or profession, e.g., fingertips in harp players, base of little finger in bundle tiers, hod carriers on shoulders, sailors on abdomen, hand type setters on fingertips, violinists on left jaw, basket makers on outer edge of palm, engravers on little finger, wood cutters on face, porters on palms and shoulders.	Callosities are often more revealing of a trade than important as disease state. Merely skin hypertrophy of fingers, hands, feet, or other local portions of body.
Skin corrugation (rugosity).	Several nonindustrial causes; outstanding cause in industry, tannins; less definitely alkalies.	In tan yards, some workers' skin of hands literally may be tanned, grossly rugose and brown discolored. From alkalies, hypertrophy with fissuring is common; somewhat dissimilar to rugosity; many other examples.	Tendency to recover on elimination of exposure; some permanent damage.
Skin hemorrhage (purpura).	Many nonindustrial causes including infection, tuberculosis, cachexia, endocarditis. In industry suspect benzol.	Always significant. R. M. I.	In benzol poisoning may be associated with bleeding from gums, nose, genitalia.
"Birthmarks."	Never industrial, and not properly "birthmarks."	Area of birthmarks sometimes more susceptible to action of industrial irritants, pressure, etc.; may become cancerous.	To eliminate disfigurement, many so-called "birthmarks" may be removed by electric needle, x-ray.

(*continued*)

Common External Marks of Occupation or Occupational Diseases or Other Diseases (*continued*)

Mark or sign	Probable cause	Significance	Comment
		Skin, *continued*	
Hypodermic skin markings.	Improper or extensive use of hypodermic needle.	Marks the hypodermic introduction of drugs, such as morphine or insulin.	Usually important to rule on the desirability of work applicants—drug addicts, diabetics. On side of chest, may be associated with collapsed lung in tuberculosis.
		Skin Patterns	
Lesion distribution.	Contact dermatitis.	Common distribution—back of hands and fingers, wrists, forearms (any surface), elbow folds, upper arms, neck and face, but not scalp; waistline, thighs, lower legs, with no or little involvement of chest or back, knees or feet. R. M. I.	Apart from traumatic injury, palms are seldom primarily involved in industrial dermatitis.
Lesion distribution.	Psoriasis.	Elbow points, knee caps, palms, back of head, shins, abdominal wall. R. M. I.	This distribution almost rules out all industrial dermatitis.
Lesion distribution.	Cutaneous syphilis.	Characteristic distribution—palms, cheeks, forehead, chest, abdomen, genitalia, anal region, soles of feet. R. M. I.	Almost opposite that of industrial dermatitis.
Lesion distribution.	Erythema multiforme (papular erythema).	Characteristic distribution—back and front of hands but not fingers; front of wrists, around elbows, around mouth, forehead, rarely on torso, rarely on thighs, front of knees, front of feet. R. M. I.	This distribution varies greatly.
Lesion distribution.	Acne.	Shoulders, chest, neck, face but not scalp, back.	Lesions and distribution quite dissimilar to industrial dermatitis.

Lesion distribution.	Shingles (herpes zoster).	Characteristic distribution follows nerve courses; front of arms, forehead and upper face, obliquely on chest and abdomen, outer surface of thighs, rarely around shoulders, rarely below knees. R. M. I.	Associated with much more pain than many forms of dermatitis.
Lesion distribution.	Seborrhea (on oily skin).	Scalp, forehead, sternal region, armpits, midway between shoulders, genital region; practically never on back or abdomen.	Seborrhea on dry skin may have different distribution and chiefly involves extremities.
Lesion distribution.	Scabies (itch).	Webbing between fingers, palms of hands, armpits, breasts in women, around and on genitalia, between buttocks. R. M. I.	Less frequent on lower extremities.
Lesion distribution.	Mycotic dermatitis (ringworm).	Palmar surfaces of fingers and hands including webbing of fingers, but seldom backs of fingers and hands, forearm, scalp, bearded region, midsection of chest (certain varieties), around genitalia, anal region, between toes, soles of feet, around ankles. R. M. I.	Fungal lesions as seen in industry seldom are characterized by the circular involvement with clearing center.
		Eyes	
Blindness (in industry usually partial).	Arsenic, benzol, carbon monoxide, hydrocyanic acid, hydrogen sulfide, lead, methanol, nitroglycerin, tobacco, trauma; many nonindustrial causes.	The pathology of industrial blindness as occupational diseases varies highly; e.g., from methanol, optic neuritis; from benzol, intraocular hemorrhage. R. M. I.	Many other substances than those listed may impair vision.
Cataracts.	Usually not an occupational disease, but traditionally associated with glass making, furnace work, and other incandescent operations. Common from penetrating foreign bodies around lens. Frequently congenital, and frequent among diabetics.	Disappearing as an occupational disease. R. M. I.	Use of suitable eye protection in hot and excessively luminous industries is preventing the occurrence of cataracts.

(continued)

Common External Marks of Occupation or Occupational Diseases or Other Diseases (*continued*)

Mark or sign	Probable cause	Significance	Comment
	Eyes, *continued*		
Conjunctivitis.	Almost unlimited; nonindustrial and industrial agents, such as vapors, acids, dust, ultraviolet rays (Klieg eye).	Seek out particular cause. Frequently associated with respiratory tract inflammation. R. M. I.	One of commonest manifestations of industrial irritants. One red eye more likely to be industrial than two red eyes.
Conjunctival xerosis (dry eye).	Vitamin A deficiency.	Thickening of conjunctivae over eyeball; vascular injection with growth over corneal margin in severe cases.	More general distribution than pterygium.
Exophthalmus (protruding eyes).	Usually bilateral from hyperthyroidism; monolateral from brain or eye tumors.	Commonly unrelated to work exposure; causes staring expression. R. M. I.	Associated with tremors, sweating, flushed skin, agitation, other aspects of thyroid syndrome.
Discoloration of eyes (blue sclera).	Familial disease unrelated to work.	Part of well-established syndrome of brittle bones and blue sclera.	For confirmation, observe other members of the family.
Discoloration of eyes (yellow sclera).	Usually jaundice.	Reflects liver damage possibly from industrial causes, such as carbon tetrachloride, or instead, infection or cancer. R. M. I.	Look for jaundice of skin or bile in urine.
Discoloration of eyes (slaty grey sclera).	Part of picture of argyria.	Produced by silver.	Does not always occur in argyria.
Discoloration of eyes (purple sclera).	Methyl violet.	External entry of traces of indelible pencil. R. M. I.	Methyl violet, in addition to abnormal coloration, may induce definite irritations and rarely ulcers. Temporary.
Discoloration of eyes (mineral specking).	Several mineral dusts.	Various mineral dusts, such as iron, mercury, calcium, may induce spotty, colored deposits; color depends upon metal.	Does not always arise in presence of mineral or metal dusts; black specks also produced among workers melting sealing wax; also phenol.
Discoloration of eyes (misc.).	Various dyes and other industrial and therapeutic agents; lack of vitamins.	Relatively unimportant; staining of eyes from accidental or deliberate introduction of divers agents.	Usually unimportant and temporary except in avitaminosis.
Arcus senilis.	Usually old age.	White circle or arc at periphery of cornea.	May occur in premature old age.
Impairment of color vision (temporary—not color blindness).	Few drugs, such as santonin, tobacco.	Temporary loss of color judgment.	Santonin possibly may discolor eye humors.

Restriction of color field.	Chlorinated hydrocarbons; possibly other substances.	Does not appear as a visible sign; attracts attention on complaint of worker. R. M. I.	More frequently from nonindustrial causes.
Diplopia (double vision).	Usually nonindustrial, but may be caused by emetine and possibly other substances.	R. M. I.	Common feature of alcoholism.
"Doll's eye."	Postdiphtheritic paralysis.	Dissociated movements of head and eyes; when head is raised, the eyes are lowered, etc.	Sometimes associated with protruding eyeballs.
Impaired movement of eyes or lids.	Many nonindustrial causes; may be a feature of some industrial diseases as lead poisoning.	Many types of paralysis. R. M. I.	Droopy eyelids, hollow cheeks, fatigued expression, suggests myasthenia gravis.
Nystagmus (fine repetitive motions of eyeballs).	Neuroses; fatigue, ear disease.	Fairly frequent among miners, train dispatchers, jewelers, draftsmen. R. M. I.	Eye motion may be lateral, vertical, circular or combined.
Deposits in or around eyelids (misc.).	Deposits of fat, pus, fibrous tissue or pigment.	May represent abscesses, cysts, or calcareous formations; many varieties.	Certain deposits suggest diabetes or gout.
Pterygium.	External chemical or mechanical repeated minor injuries.	Wedge-shaped film growing from angle of eye toward and sometimes covering cornea; resembles eye condition in certain avitaminoses. R. M. I.	Occurs among lime burners, stonecutters, masons, sand blasters, and here noted for first time, varnish cookers.
Intrascleral hemorrhage	Rupture of minute blood vessel with filming of blood between scleral layers.	Alarming bright red in appearance, but usually without medical importance. May be related to high blood pressure.	Goes through usual stages of ecchymotic clearing, that is, purple, yellow, etc.
Puffiness of eyelids.	May be early sign of arsenic poisoning.	Frequently associated with other characteristics of eye or respiratory infection. R. M. I.	Observe for additional swelling above eyebrows. If not infection, establish possibilities of arsenic exposure.
Cloudy cornea.	Usually unrelated to work.	May represent beginning glaucoma. R. M. I.	Usually associated with foggy vision, severe pain in eye, dilated pupil, swelling of conjunctivae and lids.
Pearly sclera	Pearly white or pearly blue sclera, usually associated with anemia.	May be associated with occupational anemias. Highly brilliant eyes produced by drugs, and especially in women. R. M. I.	Frequently suggests anemia, particularly when conjunctivae are pale pink.
Photophobia (intolerance of light).	Eye strain.	May indicate uncorrected defects in vision. R. M. I.	In industry may be related to excess light, either natural or artificial. Glare.

(continued)

Common External Marks of Occupation or Occupational Diseases or Other Diseases (*continued*)

Mark or sign	Probable cause	Significance	Comment
		Nose	
Rhinitis—"running nose."	Infection or chemical irritation of nasal passages.	Obviously one of commonest nonoccupational affections and one feature of irritation from numerous industrial gases, vapors, dusts, etc.	Rhinitis may appear on an allergic basis from both industrial and nonindustrial causes.
Rhinophyma (bulbous nose).	Related to acne rosacea.	Hypertrophy of nose and nearby tissues; not associated with industry.	Sometimes associated with alcoholism; largely unproved.
"Saddle-nose."	Congenital syphilis.	May be due to trauma.	May occur in acquired syphilis.
Infected nodules with severe systemic disease.	Glanders.	Rare disease commonly limited to horse tenders. R. M. I.	Nodules discharge yellow, glary pus with offensive odor.
Nose bleed (epistaxis).	Many nonindustrial causes. If industrial, caused by irritant gases, dusts, or mists such as chromic acid, benzol, or fluorides.	If profuse and repeated, R. M. I.	May be associated with foreign bodies in nose, deviated septum, many infectious diseases, such as measles, various forms of anemia, cancer, etc.
		Ears	
"Cauliflower" ears.	Trade-mark of the pugilist.	Fibrous deposits in external ear.	In the absence of protection, may arise among military tank operators.
Noise deafness (cocked good ear is the visible sign, or attitude may indicate deafness).	Noise.	Temporary or permanent deafness or impaired hearing to some or many frequencies; probably originates on a fatigue basis followed by organic impairment. R. M. I.	Usually bilateral, even when one ear is protected against noise. Deafness in one ear, if occupational, may arise in train dispatchers, telephone operators, etc.
Deafness (impaired hearing other than from noise).	Various substances, such as lead, hydrogen sulfide, carbon disulfide, are credited with capacity to produce deafness.	Often difficult to differentiate between industrial and nonindustrial deafness; normally occurs in old age. R. M. I.	Deafness may constitute a neurosis.
Impacted cerumen (wax-plugged ears).	Ear wax as such, or mixed with dusty materials.	Common minor affliction in and out of industry, particularly dusty trades; signs of hearing impairment constitute mark. R. M. I.	Readily may be remedied by softening and washing.

Aural dermatitis (ear itch).	Varied; external irritants, infection, systemic impairment, lack of vitamins.	The ears are common sites for many forms of dermatitis and other dermatoses. R. M. I.	Noise-preventing and hearing appliances may favor aural dermatitis. Ear scratching prominent sign.
Otitis media (running ears).	Infection.	Common ear disease of all ages; frequent in industry, but not often caused by it. R. M. I.	A frequent source of subsequent deafness.
Equilibration disturbances (Ménière's disease).	Dysfunction of semicircular canals. Falling without obvious cause is the objective sign.	Any defect of equilibration of grave importance in airplane operators. R. M. I.	Probably related to sea sickness, train sickness, etc.
Gangrene.	In industry, frostbite.	In absence of history of frostbite, suspect diabetes. R. M. I.	May be caused by infection.
Tophi.	Gout.	Characterized by numerous hard, yellowish, round, pointed nodules at ear margin.	Similar nodules may appear on various portions of body, such as feet.
Increased hearing (overirritation by noise).	Alcohol and/or tobacco poisoning.	Pathologic irritation by moderate noise.	Also caused by certain neuroses, quinine and salicylic acid poisoning, and migraine.
		Lips, Mouth, Teeth, Tongue, Neck	
Cornification of lips (thickening of lips).	Mechanical pressure and friction on lips.	Characteristic of many trades or professions, such as wind instrument players, glass blowers, etc.	Nondisabling.
Lips (cancer, epithelioma).	Exact cause unknown.	The lips are perhaps the most common site of epithelioma. R. M. I.	Rarely related to industry as the cause; said to be common in fishermen from tar on fish nets and the holding of net thread between lips.
Cheilosis (one form of inflammation of lips).	Vitamin B deficiency.	Pallor of lips with maceration of mucosa; may be one indication of vitamin lack.	Common among industrial workers; not directly related to work as a cause.
Rhagades.	Congenital syphilis.	Fissured inflammation, or scars therefrom at angles of mouth.	Not to be confused with cheilosis from vitamin deficiency.
Tongue (scars from epileptic tongue biting).	Epilepsy.	Some epileptics will present evidence of fresh or healed damage of the tongue from biting during seizures. R. M. I.	Evidence of tongue chewing does not constitute proof of epilepsy.
Coated tongue.	Constipation, gastritis, dehydration.	Relatively unimportant.	Rarely coated tongue in colors such as black may be due to fungal infection.

(continued

Common External Marks of Occupation or Occupational Diseases or Other Diseases (*continued*)

Mark or sign	Probable cause	Significance	Comment
	Lips, Mouth, Teeth, Tongue, Neck, *continued*		
Herpes (labial)—"cold sores."	Due to action of a virus.	Virus probably always present but only becomes active under unfavorable conditions such as infection.	Not to be confused with labial chancre.
"Beefy" tongue.	Vitamin B deficiency.	One manifestation of vitamin B lack. R. M. I.	Enlarged tongue, roughened, rugose and red; somewhat resembles raw beef.
Discolored gums.	Various metal or mineral deposits, tobacco stain, etc.	The purple gum line of lead absorption, the similar line from bismuth, the blue line following trinitrotoluene exposure or poisoning, purple line from copper, bluish line from mercury or zinc, purple gums from scurvy. R. M. I.	Lines or discoloration of gums are not conclusive proof of any occupational disease.
Dental erosions.	Erosion from chemicals, such as from acids or mechanical erosion such as from glass blowers' pipes; numerous variations; specific variations for many trades, such as battery makers from acid, sewers from thread biting, wind instrument players, "tack spitters," brush makers who trim bristles by biting, pencil chewers in offices.	Profoundly eroded teeth of acid workers seldom decayed and are not painful.	Apart from dental erosion constituting a sign of occupational damage in many trades, the premature loss of teeth may possibly be related to work as a contributory cause.
"Mulberry molars."	Congenital syphilis.	Dome-shaped, stunted first molars due to overgrowth of enamel.	Various other dental defects suggest congenital syphilis.
Hutchinson's teeth.	Congenital syphilis.	Notched incisors with narrow edges and peg topped.	May be associated with impaired hearing and baked cornea.
Discolored and mottled teeth.	Fluorine is the cause of characteristic mottling, but many metals such as copper and iron bring about diffused coloration.	Apparently no great harm produced by many forms of teeth coloration.	Smoking, and particularly pipe smoking, may lead to black deposits on teeth.
Speech defects (not visible defects).	Highly varied causes—brain tumors, syphilis, neuroses, fatigue, etc.	Stammering, slurred speech, monotonous speech, explosive speech, aphonia, etc. R. M. I.	Stammering may be related to improper management in childhood of left-handedness.

Goiter (hyperthyroidism).	Enlarged thyroid gland.	Common as simple goiter due to iodine deficiency. Also toxic goiter from hyperthyroidism. R. M. I.	More common in women.
Salivation.	Industrial causes—mercury, potassium chlorate, phosphorous, copper, bromides.	Excessive formation of saliva. R. M. I.	Scores of nonindustria causes, such as Vincent's angina, mumps, cancer, syphilis, scurvy, etc.
Mouth breathing (open mouth).	Numerous causes unrelated to work, such as adenoids. If associated with dyspnea, may be caused by silicosis, which is rare.	Mouth breathing may be caused by nasal obstruction. R. M. I.	If related to recent injury to face, suspect dislocation of jaw.
Swollen tongue.	If industrial, suspect ingestion of corrosive poison, phenol, cresol, mineral acids, mercury, etc.	Many causes unrelated to work, such as cretinism, infection, cancer, actinomycosis. R. M. I.	When due to industrial material, usually accidental or suicidal.
	Chest		
Bulging of breast bone (sternum).	If associated with pulsation, suspect aneurysm; if chicken-breast-like, suspect rickets; if series of knobs on either side at rib section, suspect rickets.	Any marked external protrusion should lead to medical observation.	Converse picture that of depressed sternum frequently called "cobbler's chest" associated with shoemakers' trade as cause.
	Extremities Apart from Skin		
Ganglion (ganglia).	Cysts in the region of joint capsules and tendon sheaths.	May occur along any tendon sheath or about many joints but more common on hands and feet; may be either industrial or nonindustrial.	Frequently attributed to coarse vibration as from pneumatic tools.
Bursitis (excess fluid around joints).	Friction, pressure, or infection.	Bursae are potential spaces in connective tissue around joints that grow in response to functional demand. R. M. I.	Many varieties constitute occupational diseases, as in "beat elbow" in miners.
Clubbed fingers.	Congenital, or may be related to heart disease.	Various occupations lead to some bulbing of finger ends from hypertrophy; cause of the relationship to silicosis and heart disease obscure.	Many other variations in shape of fingers. Toes may be clubbed.

(continued)

Common External Marks of Occupation or Occupational Diseases or Other Diseases (*continued*)

Mark or sign	Probable cause	Significance	Comment
	Extremities Apart from Skin, *continued*		
Joint enlargement (arthritis).	Usually infection and gout.	Bony enlargement frequently called rheumatism, usually in error; ordinarily represents reaction to infection or infection products.	Some occupational diseases, such as lead poisoning, infrequently lead to bone and joint enlargement.
Varicose veins.	Hydrostatic pressure, infection among others.	May appear anywhere, but most common in lower extremities; little related to work as a cause.	Frequently associated with indolent ulcers.
Flat feet (pes plenus).	May be congenital; may result from weight bearing; may be related to degeneration of senility.	A well-known common affection important to industry but little caused by it.	May be influenced for good or bad respectively by good or poor footwear.
Saber shins.	Congenital syphilis.	Forward bending and thickening of middle third of tibia.	Knobby shin bones in absence of saber deformity also suggests syphilis.
Wrist drop (wrist weakness).	Metal poisoning, usually lead or arsenic, or alcohol.	A frequent feature of lead poisoning; its counterpart is ankle drop; seen in lead poisoning when leg muscles are much used. R. M. I.	Many other muscle groups similarly may be weak in metal poisoning, and chiefly in lead poisoning.
Tremors.	Different causes for different types.	Many types involving many portions of the body from fingers to tongue. May be related to various diseases and states, including fear, goiter, Parkinson's disease, lead poisoning, etc. R. M. I.	Some tremors cease on the accomplishment of an intention; thus a marked tremor may exist in reaching for a book and cease when the book is picked up.
Dead fingers (white fingers).	Cold associated with vibration.	This condition is akin to several others involving capillary blood supply to fingers; some conditions unrelated to cold or vibration, such as Buerger's disease. R. M. I.	Has occurred among marble cutters working with vibrating tools in cold weather in outside sheds; persists for months.

Writer's cramp.	At times, a neurosis; at times caused by local fatigue.	When apart from neurotic influence, writer's cramp constitutes a good example of localized fatigue; ordinarily involves those fingers and those muscles employed in any particular form of writing. R. M. I.	Cramplike pains may occur. Actual site of damage not in fingers but in arm.
Stereo movements.	Habit; continuation of work movements after work.	In some occupations requiring highly repetitive small motions, these motions are continued long after work hours. No disability, but some significance related to monotony effects, etc.	Well presented years ago in famous comic motion picture.
Baseball finger.	Blow by baseball on end or palmar surface of finger.	Somewhat characteristic swelling and deformity, usually limited to one joint of one or more fingers.	Common among industrial workers and fairly common basis of claims for compensation.
Dupuytren's contraction.	Shortening of the palmar fascia.	Permanent flexion of little and ring fingers (at times all fingers) with rigidity of palmar tissue. May be caused by infection, may result from oft-repeated severe pressure on palm. Said to be common among upholsterers.	Rare before middle age. Associated with arthritis.
Trigger finger (snap finger).	Injury to fingers in or out of industry.	Difficulty in extending fingers, but after great effort fingers fly out like jackknife blade.	A corresponding condition may exist in toes.
Sclerodactylia (deformed, pigmented fingers).	Unknown, but probably unrelated to work.	One, and usually more, fingers of both hands become withered, shortened, deformed, nodular, waxy-white, and at times brown or black pigmented. R. M. I.	Much worse in cold weather.

(continued)

Common External Marks of Occupation or Occupational Diseases or Other Diseases (*continued*)

Mark or sign	Probable cause	Significance	Comment
	General and Miscellaneous		
Edema.	Immediate cause—increased fluid in tissue.	Edema may occur in any tissue, organ, or system from ankles to eyelids. Ordinarily not a disease in itself. R. M. I.	Edema around ankles after long standing in the absence of known disease may not be important.
Pathologic sleepiness (somnolence).	If organic, may be related to pituitary disease or other glandular disorders. Commoner in obese or giant-sized persons. Sometimes appears in early pregnancy.	May only represent lack of proper sleep. May be associated with alcoholism. May be a symptom of various occupational diseases. R. M. I.	Many workers, particularly on late night shifts, now indulge in drug stimulation, chiefly caffein. Many proprietary preparations available. Caffein poisoning in industry is a ready possibility.
Sunstroke.	Chiefly direct exposure to sun's heat. Less frequently artificial heat.	Represents derangement of heat-regulating system of body. R. M. I.	Chief characteristics—high body temperature, hot dry skin, loud breathing, unconsciousness; in early stage eye pupils dilated, later contracted.
Myxedema (hypothyroidism).	Lowered functioning of thyroid gland.	More frequent among women. R. M. I.	Characterized by dull, heavy features, thickened, swollen skin, some loss of hair, subnormal temperature, sleepiness, joint pains, constipation.
Shaking palsy.	Unknown.	Rare before middle age. R. M. I.	Chief features—shaking of head, tremors of hand and arms, muscular rigidity, masklike facies, propulsive gait; some similarity to manganese poisoning.
Barrel-shaped chest.	Common among asthmatics, fairly common among glass blowers, less frequent among musicians, i.e., singers, wind instrument players.	Associated with pulmonary emphysema (dilation of lung sacs). R. M. I.	During asthmatic attack, there may be either skin pallor or cyanosis, anxious facies, violent respiratory movement, short inspiration, long, wheezy expiration.

Tics.	Spasmodic contraction of any portion of body, such as cheek, tongue, eyelid, fingers. Not directly related to industry.	Common among neurotics.	Tics are frequently called "habit spasms."
X-ray gangrene.	Improper x-ray exposure.	Begins like common skin burn but advances to deep ulceration and sloughing. Usually involves fingers and hands. R. M. I.	Common among older x-ray workers and technicians. Frequently seen among factory workers and industrial workers as a result of poor x-ray treatment for dermatoses.
Phenol gangrene.	Extensive or prolonged contact with concentrated carbolic acid (phenol).	Following accidental and painless contact with carbolic acid, fingers, hands or other parts become brown, dry, shriveled, and finally black, with possible eventual spontaneous amputation. R. M. I.	May arise apart from industry from accident or poor medication.

(continued)

Common External Marks of Occupation or Occupational Diseases or Other Diseases (*continued*)

Mark or sign	Characteristics
Abnormalities of gait.	The manner of walking, together with the carriage of the entire body, may afford a true insight into precise disease states, or at least may indicate abnormality to the point that a medical investigation should be carried out. It is difficult to describe in a few words the peculiarities of gait, even though on observation abnormality be quite obvious. For this reason, resort to tabular presentation is for the moment abandoned. Many peculiarities of gait call for no description since the provoking cause is at once evident. Such, for example, are the waddling gait of the woman in advanced pregnancy, the worker with an artificial leg, the victim of a stiff knee, the many types of gait abnormality following infantile paralysis, the gait occasioned by shortening of one limb, the tottering, generally unstable gait characteristic of senility or convalescence from disease. In other states, some of which are clearly occupational, gaits, while characteristic, may be less obvious as to cause. In any peripheral neuritis of the lower limb, e.g., from *lead* or *arsenic*, the resulting ankle drop or weakness may lead to a revealing gait. In such instances the leg is lifted high with exaggerated knee action, the foot is thrown forward, and the ground or floor is slapped at each step. The shoe is worn at the toe. Although the condition is commonly bilateral, when unilateral an obvious variation is induced. The gait of the worker under the influence of *alcohol* exposes his condition. The gait is staggering, tottering, reeling. Alternately the body may be leaned forward, backward or sideward with purposeless lurching. The drunk, apparently about to fall with each step, rarely does so. The gait in *manganese* poisoning is called the "rooster gait." There is propulsion with ever-increasing rapidity, until the victim may catch himself on some support; otherwise he may fall. If he starts backward, retropulsion becomes the obvious counterpart of propulsion. In some forms of central nervous system *syphilis*, the gait is ataxic. The patient walks with his eyes on the ground, and in some severe circumstances may not walk without seeing every step. Manifestly, this gait is worse at night, and some patients with this disease fall to the ground whenever their eyes are closed. In this gait, the feet are turned out and the legs are far apart. The leg movements are excessive and the feet lifted too high. In this instance, the heels come down sharply, as may be proved by unusual wear on the heel. When one leg is paralyzed, as in *hemiplegia*, the afflicted leg is rigid and moves as a part of the body as a whole. The leg is thrown outward, swinging in a semicircle and with a motion toward the trunk. Thus, shoes will be worn down on the outer side. In *palsy* (paralysis agitans), the steps are short and shuffling, with a tendency to walk faster and faster, as in manganese poisoning. This gait may be accompanied by a variety of tremors of hand and head, and is associated with a characteristic speech. In *sciatica*, the afflicted leg is kept in a position of slight bending with the heel raised and in walking, the chief pressure on that side is limited to the front part of the shoe, which part shows most wear. Many *epileptics* exhibit no gait peculiarities, but some in well-established instances have a gait characterized by slouching and apparent weakness.

Abnormalities of gait (*continued*)	In *Huntington's chorea*, a rare disease, the gait is associated with motion in all parts of the body. The arms, head, and legs move from side to side, as well as forward. There is continuous rocking and lurching with flinging motions interspersed with momentary periods in which the whole body is at a standstill.
	In *hysteria* and *malingering* involving the lower extremities, the assumed gait may be so bizarre as to arouse suspicion that no organic lesion exists. Variations are almost limitless. One neurotic may push an imaginary lame leg along as though on a skate; another may drag the foot with the top of the toes downward; another may walk on the outer edge of one or both feet. Occasionally the motion made may suggest the arc of a scythe. All of these gaits possess some feature apart from the characteristic gait of any organic lesion.
	In *mercury* poisoning there may be no involvement of a lower extremity, but on occasion may be characterized as a running gait.
	At least 50 other conditions unrelated to work as a cause, but occurring among workers, may be observed ranging from the ordinary limp due to corns, injury, gout, inguinal or pelvic abscess, to the complex gait of Thomsen's disease in which the legs are alternately stiff.
Abnormalities of facies.	The countenance may in itself disclose disease states, some few of which may be related to occupation. The most characteristic peculiarities of facies are related to disabling diseases, of a type not seen in workers on duty, for example, the facies of typhoid fever. Some facies that may give clue to diagnosis are now mentioned.
	In the *dyspneic* facies, the mouth is open, the lips are dry, the nares dilate with each inhalation. The face may possess a bluish pallor, the expression is one of anxiety. This condition might be found in well-established silicosis, in heart disease, and in some types of asphyxiation.
	Manganese facies may be characterized as masklike. The skin is without wrinkles, the countenance without expression and comparatively motionless—doll's face. Other diseases of the central nervous system may give rise to masklike facies.
	In the presence of *adenoids*, and more particularly in persons younger than those in industry, the face is likely to be long and hatchetlike, the expression is dull, the nares pinched, the mouth open and prominent, the lips dry, the eyelids droop.
	The facies of congenital *syphilis* are characteristic in adults. The forehead is overhanging and bumpy, the bridge of the nose is depressed (saddle nose), linear scars radiate from the angles of the mouth. Hutchinson's teeth, elsewhere described, may be present.
	Occasionally a patient with beginning but well-established *pneumonia* may be still at work. Although the characteristic facies may not have established themselves, they, if present, will show a flushed skin, the breathing may be rapid and hurried, and possibly associated with a grunt at the end of every exhalation. Herpes may be present; the eyes glisten; the expression is that of anxiety.
	In some cases of *hyperthyroidism*, the facies continually reflect astonishment—staring facies. This is brought about by protruding eyeballs, which bare more than normal proportions of the whites of the eyes; the eyebrows may be lifted; the skin of the face may be flushed and moist.

(*continued*)

Common External Marks of Occupation or Occupational Diseases or Other Diseases (*concluded*)

Mark or sign	Characteristics
Abnormalities of facies (*continued*)	In *neurotics* and *hysterical* persons, the facies may give a hint that such states exist. The expression is characterized by amiable but silly smiling on an otherwise empty face, or instead repeated but not continuous frowning may take place in the absence of any reason for such. Irregularly these faces exhibit facial tics.
	In *shaking palsy*, the face may be so motionless as to appear neatly starched, but accompanying this there may be tremors of the entire head with eyes wide open and the eyeballs in motion. Such an expression in this disease may be accompanied by tremors of the hands or legs and a jumpy speech.
	In *thyroid deficiency*, the features are thick, coarse, broad. The face is moonlike, expressionless, and stolid; the outer third of the eyebrows may be missing or scanty; the skin is dry. "Pudgy" characterizes these facies.
	Cyanotic facies (cyanosis elsewhere mentioned) may arise from several industrial causes, as well as non-industrial. In either instance, the ears, lips, cheeks will take on a bluish-purple tinge which frequently also may be observed at the fingertips.
	Some clearly indicative facies scarcely lend themselves to verbal presentation. Thus, the chronic alcoholic reveals his intemperance by his little-describable physiognomy; so also the facies of early tuberculous meningitis, which is unlikely to be seen in industry. Of interest ordinarily limited to the physician are the revealing facies of complex central nervous system diseases, such as myasthenia, dyspituitarism, acromegaly, lenticular degeneration. etc. It is obvious that not in all and every case of the several states or diseases mentioned will the facies be so characteristic as here mentioned, which by design attempt to portray well-established conditions.

Chapter Thirteen* – Section One

Fire and Explosion Hazards of Combustible Gases and Vapors

G. W. JONES

Fires and explosions resulting from the presence of combustible gases and vapors are among the major hazards in present industrial operations. There is need for a greater appreciation of these hazards and a better understanding of means of mitigating and preventing them.

I. Limits of Inflammability

Confusion has arisen regarding the meaning of the terms "explosive limits," "inflammable limits," and "limits of inflammability." In the final analysis, these different expressions mean the same thing. Some authorities regard explosive limits as those limiting mixtures within which flame will propagate through the entire volume of the mixture and develop appreciable pressure, while inflammation limits, or limits of inflammability, are regarded as those limiting mixtures within which flame will propagate entirely through the mixture without regard as to whether pressure is produced.

It is impossible to distinguish an inflammation from an explosion by the amount of violence produced. Mixtures just within the limits of inflammability, if confined in a long tube and tested by opening one end and igniting at this open end, will propagate flame quietly and slowly through the tube (usually at a uniform speed) and the speed for a given concentration of combustibles in air will vary with the direction of flame propagation. This mixture, if confined in a closed bomb of adequate dimensions and ignited when the gases are in motion or gentle turbulence, will propagate flame at a speed several times as fast as that in the open tube and develop pressures ranging up to 30 lb. or more p.s.i. Thus it is seen that the pressure developed by an inflammable mixture depends upon the environment and direction of flame propagation; therefore, no differentiation should, or can, be made between explosive limits and limits of inflammability.

* From the Central Experiment Station, Bureau of Mines, U. S. Department of the Interior, Pittsburgh, Penna.

A. FACTORS AFFECTING THE LIMITS OF INFLAMMABILITY

Only a brief discussion of the various factors affecting the limits of inflammability will be given. A more complete discussion is given in published reports.[1–3] The limits are affected by the direction of flame propagation, the shape, diameter, and length of the test apparatus, the temperature and pressure of the mixture at the time of ignition, the percentage of water vapor present, and indirectly by the source of ignition.

Wider limits are obtained for upward propagation of flame than for horizontal or downward propagation. Therefore, the risk of an explosion is greater when the mixtures are ignited from below than when ignited from above.

The limits of inflammability are widened as the diameter of the apparatus is increased, rapidly at first and then more slowly as the diameter approaches 2 in. An apparatus greater than 2 in. in diameter gives limits very little different from those obtained with 2-in. apparatus.

The apparatus must be long enough to insure continued propagation of flame after the heat imparted to the mixture by the source of ignition has been dissipated. An apparatus 3 ft. or more in length is sufficient. It has been found that if the apparatus is closed when the mixtures are ignited and the gases are in gentle turbulence, the lower limit is reduced slightly.[4]

Ordinary variations of laboratory temperatures have no appreciable effect on the limits of inflammability. Elevated temperatures cause a widening of the limits.

Normal variations of atmospheric pressure have no appreciable effect on the limits. The effect of high pressures on the limits is neither simple nor uniform, but specific for each particular combustible. As yet, no means has been developed for predicting the effect of high pressures on the limits of inflammability for any given combustible in air or oxygen. In certain cases both limits are raised, while in others the limits are narrowed. However, increased pressure raises the upper limit of inflammability of saturated hydrocarbons.

The normal quantity of water vapor present in atmospheres at laboratory temperatures affects the lower limit of inflammability only to a slight extent. The presence of water vapor reduces the upper limit because some of the oxygen in the mixture is displaced by the water vapor. Since the oxygen concentration is the important factor in an upper-limit mixture, as the oxygen is lowered the amount of combustible that can be burned is decreased, and so the limit is lowered.

B. LIMITS OF INFLAMMABILITY OF GASES AND VAPORS IN AIR

Industrial safety requires that only those values for the limits of inflammability of gases and vapors in air be employed that have been obtained in apparatus giving the widest limits. Keeping this fact in mind, tabulations of the limits of inflammability have been reviewed and selected values given in Table 1. Values obtained in

[1] H. F. Coward, C. Carpenter, and W. Payman, *J. Chem. Soc.*, **115**, 27 (1919).

[2] H. F. Coward and G. W. Jones, *U.S. Bur. Mines Bull.* No. **279** (1939).

[3] H. F. Coward, G. W. Jones, C. G. Dunkle, and B. E. Hess, *Mining Met. Invest., Carnegie Inst. Tech. Co-op. Bull.* No. **30** (1926).

[4] G. W. Jones, E. S. Harris, and W. E. Miller, *U.S. Bur. Mines Tech. Paper* No. **544** (1933).

TABLE 1

Limits of Inflammability of Gases and Vapors in Air

Name	Formula	Limits of inflammability, percentage (by volume).				Percentage by volume combustibles in air. Mixture for theoretical complete combustion	Ratio of lower limit to P.C.C.[a] Column 3 ÷ 5	Ratio of upper limit to P.C.C.[a] Column 4 ÷ 5
		Lower	Ref. No.	Upper	Ref. No.			
(1)	(2)	(3)		(4)		(5)	(6)	(7)
Paraffin Hydrocarbons								
Methane	CH_4	5.00	4	15.00	4	9.47	0.53	1.58
Ethane	C_2H_6	3.10	5	12.45	3	5.64	0.55	2.21
Propane	C_3H_8	2.10	6	10.10	6	4.02	0.52	2.51
Butane	C_4H_{10}	1.86	3	8.41	3	3.12	0.60	2.70
Isobutane	C_4H_{10}	1.80	7	8.44	7	3.12	0.58	2.71
Pentane	C_5H_{12}	1.40	7	7.80	7	2.55	0.55	3.06
Isopentane	C_5H_{12}	1.32	8	—	—	2.55	0.52	—
Hexane	C_6H_{14}	1.25	7	6.90	7	2.16	0.58	3.19
Heptane	C_7H_{16}	1.00	9	6.00	9	1.87	0.53	3.21
Octane	C_8H_{18}	0.95	7	3.20*	9	1.65	0.58	1.94
Nonane	C_9H_{20}	0.83	10	2.90*	9	1.47	0.56	1.97
Decane	$C_{10}H_{22}$	0.67*	9	2.60*	9	1.33	0.50	1.95
Dodecane	$C_{12}H_{26}$	0.60*	9	—	—	1.12	0.54	—
Tetradecane	$C_{14}H_{30}$	0.50	9	—	—	0.96	0.52	—
Olefins								
Ethylene	C_2H_4	2.75	11	28.60	11	6.52	0.42	4.39
Propylene	C_3H_6	2.00	7	11.10	7	4.44	0.45	2.50
Butadiene	C_4H_6	2.00	12	11.50	12	3.67	0.54	3.13
Butylene	C_4H_8	1.98	13	9.65	13	3.37	0.59	2.86
Amylene	C_5H_{10}	1.65	14	7.70	14	2.72	0.61	2.84
Acetylenes								
Acetylene	C_2H_2	2.50	7	80.00	15	7.72	0.32	10.36
Allylene	C_3H_4	1.74	9	—	—	4.97	0.35	—
Aromatics								
Benzene	C_6H_6	1.35	13	6.75	7	2.72	0.50	2.49
Toluene	C_7H_8	1.27	16	6.75*	17	2.27	0.56	2.97
Styrene	C_8H_8	1.10*	18	6.10*	18	2.05	0.54	2.98
o-Xylene	C_8H_{10}	1.00	9	6.00*	9	1.95	0.51	3.08
Naphthalene	$C_{10}H_8$	0.90*	9	—	—	1.71	0.53	—
Anthracene	$C_{14}H_{10}$	0.63*	9	—	—	1.25	0.50	—
Cyclic Hydrocarbons								
Cyclopropane	C_3H_6	2.45	19	10.45	19	4.44	0.55	2.25
Cyclohexene	C_6H_{10}	1.22*	20	4.81*	20	2.40	0.51	2.00
Cyclohexane	C_6H_{12}	1.33	21	8.35*	21	2.27	0.59	3.68
Methylcyclohexane	C_7H_{14}	1.15	22	—	—	1.95	0.59	—
Terpenes								
Turpentine	$C_{10}H_{16}$	0.80*	9	—	—	1.47	0.54	—

*Determinations made at elevated temperatures.

[a]P.C.C. = Per cent combustible in air. Mixture for theoretical complete combustion.

NOTE: See end of table for bibliographic reference notes.

TABLE 1, *Continued*

Limits of Inflammability of Gases and Vapors in Air

Name	Formula	Limits of inflammability, percentage (by volume).				Percentage by volume combustibles in air. Mixture for theoretical complete combustion	Ratio of lower limit to P.C.C.[a] Column 3 ÷ 5	Ratio of upper limit to P.C.C.[a] Column 4 ÷ 5
		Lower	Ref. No.	Upper	Ref. No.			
(1)	(2)	(3)		(4)		(5)	(6)	(7)
				Alcohols				
Methyl alcohol	CH_4O	6.72	6	36.50*	17	12.24	0.55	2.98
Ethyl alcohol	C_2H_6O	3.28	16	18.95*	23	6.52	0.50	2.91
Allyl alcohol	C_3H_6O	2.52	6	18.00*	6	4.97	0.51	3.62
Propyl alcohol	C_3H_8O	2.15	6	13.50	6	4.44	0.48	3.04
Isopropyl alcohol	C_3H_8O	2.02*	24	——	—	4.44	0.45	——
Propylene glycol	$C_3H_8O_2$	2.62*	14	12.55*	14	4.97	0.53	2.53
Butyl alcohol	$C_4H_{10}O$	1.70	9	——	—	3.37	0.50	——
Isobutyl alcohol	$C_4H_{10}O$	1.68	10	——	—	3.37	0.50	——
Amyl alcohol	$C_5H_{12}O$	1.19	10	——	—	2.72	0.44	——
Isoamyl alcohol	$C_5H_{12}O$	1.20	9	——	—	2.72	0.44	——
Triethylene glycol	$C_6H_{14}O_4$	0.89*	14	9.20*	14	2.72	0.33	3.39
				Aldehydes				
Acetaldehyde	C_2H_4O	3.97	17	57.00*	17	7.72	0.51	7.38
Crotonaldehyde	C_4H_6O	2.12	6	15.50*	6	4.02	0.53	3.86
Butyraldehyde	C_4H_8O	2.47	6	——	—	3.67	0.67	——
Furfural	$C_5H_4O_2$	2.10*	25	——	—	4.02	0.52	——
Paraldehyde	$C_6H_{12}O_3$	1.30	9	——	—	2.72	0.48	——
				Ethers				
Methyl ethyl ether	C_3H_8O	2.00	9	10.10	9	4.44	0.45	2.27
Diethyl ether	$C_4H_{10}O$	1.85	11	36.50	11	3.37	0.55	10.83
Divinyl ether	C_4H_6O	1.70	26	27.00	26	4.02	0.42	6.72
				Ketones				
Acetone	C_3H_6O	2.55	4	12.80	4	4.97	0.51	2.58
Methyl ethyl ketone	C_4H_8O	1.81	7	9.50*	7	3.67	0.49	2.59
Methyl propyl ketone	$C_5H_{10}O$	1.55	7	8.15*	7	2.90	0.53	2.81
Methyl butyl ketone	$C_6H_{12}O$	1.22	7	8.00*	7	2.40	0.51	3.33
Methyl isobutyl ketone	$C_6H_{12}O$	1.35	6	7.60*	6	2.40	0.56	3.16
				Acids				
Acetic acid	$C_2H_4O_2$	4.05	27	——	—	9.47	0.43	——
Hydrocyanic acid	HCN	5.60	28	40.00	28	14.34	0.39	2.79
				Esters				
Methyl formate	$C_2H_4O_2$	5.05	29	22.70*	29	9.47	0.53	2.40
Ethyl formate	$C_3H_6O_2$	2.75	6	16.40*	30	5.64	0.49	2.91
Methyl acetate	$C_3H_6O_2$	3.15	6	15.60*	6	5.64	0.56	2.77
Ethyl acetate	$C_4H_8O_2$	2.18	16	11.40*	17	4.02	0.54	2.84
Propyl acetate	$C_5H_{10}O_2$	1.77	6	8.00*	6	3.12	0.57	2.56
Isopropyl acetate	$C_5H_{10}O_2$	1.78	6	7.80*	6	3.12	0.57	2.50
Cellosolve acetate	$C_6H_{12}O_3$	1.71	9	——	—	2.72	0.63	——
Butyl acetate	$C_6H_{12}O_2$	1.39	6	7.55*	6	2.55	0.55	2.96
Amyl acetate	$C_7H_{14}O_2$	1.12*	6	——	—	2.16	0.52	——
Ethyl nitrate	$C_2H_5NO_3$	3.80	10	——	—	10.68	0.36	——
Ethyl nitrite	$C_2H_5NO_2$	3.01	17	50.00	17	8.51	0.35	5.88

*Determinations made at elevated temperatures.

[a]P.C.C. = Per cent combustible in air. Mixture for theoretical complete combustion.

NOTE: See end of table for bibliographic reference notes.

TABLE 1, *Continued*

Limits of Inflammability of Gases and Vapors in Air

Name	Formula	Limits of inflammability, percentage (by volume). Lower	Ref. No.	Upper	Ref. No.	Percentage by volume combustibles in air. Mixture for theoretical complete combustion	Ratio of lower limit to P.C.C.[a] Column 3 ÷ 5	Ratio of upper limit to P.C.C.[a] Column 4 ÷ 5
(1)	*(2)*	*(3)*		*(4)*		*(5)*	*(6)*	*(7)*
Hydrogen								
Hydrogen	H_2	4.00	31	74.20	32	29.50	0.14	2.52
Deuterium	De	4.90	33	75.00	33	29.50	0.17	2.54
Oxides								
Carbon monoxide	CO	12.50	1	74.20	32	29.50	0.42	2.52
Ethylene oxide	C_2H_4O	3.00	34	80.00	34	7.72	0.39	10.36
Propylene oxide	C_3H_6O	2.00	35	22.00	35	4.97	0.40	4.43
Acetic anhydride	$C_4H_6O_3$	2.67*	13	10.10*	13	4.97	0.54	2.03
Dioxane	$C_4H_8O_2$	1.97*	36	22.25*	36	4.02	0.49	5.53
Diethyl peroxide	$C_4H_{10}O_2$	2.34	23	———	—	3.67	0.64	———
Acetal	$C_6H_{14}O_2$	1.65*	18	———	—	2.40	0.69	———
Nitrogen Compounds								
Ammonia	NH_3	15.50	37	26.60	38	21.82	0.71	1.22
Cyanogen	C_2N_2	6.60	39	42.60	39	9.47	0.70	4.50
Acrylonitrile	C_3H_3N	3.05	40	17.00*	40	5.29	0.58	3.21
Pyridine	C_5H_5N	1.81	17	12.40*	17	3.24	0.56	3.83
Quinoline	C_9H_7N	1.21*	41	———	—	1.91	0.63	———
Nicotine	$C_{10}H_{14}N_2$	0.75*	42	4.00*	42	1.53	0.49	2.61
Sulfur Compounds								
Carbon disulfide	CS_2	1.25	7	50.00	17	6.52	0.19	7.67
Hydrogen sulfide	H_2S	4.30	15	45.50	15	12.24	0.35	3.72
Carbon oxysulfide	COS	11.90	43	28.50	43	12.24	0.97	2.33
Ethyl mercaptan	C_2H_6S	2.80	44	18.20	44	4.44	0.63	4.10
Chlorides								
Methyl chloride	CH_3Cl	8.25	45	18.70	45	12.24	0.67	1.53
Vinyl chloride	C_2H_3Cl	4.00	7	21.70	7	7.72	0.52	2.81
Ethyl chloride	C_2H_5Cl	4.00	45	14.80	45	6.52	0.61	2.27
Propyl chloride	C_3H_7Cl	2.60	6	11.10*	6	4.44	0.59	2.50
Allyl chloride	C_3H_5Cl	3.28	14	11.15*	14	4.97	0.66	2.24
Chlorobutene	C_4H_7Cl	2.02	13	9.25*	13	3.67	0.55	2.52
Butyl chloride	C_4H_9Cl	1.85	6	10.10*	6	3.37	0.55	3.00
Isobutyl chloride	C_4H_9Cl	2.05	6	8.75*	6	3.37	0.61	2.60
Amyl chloride	$C_5H_{11}Cl$	1.60	6	8.63*	6	2.72	0.59	3.18
Monochlorobenzene	C_6H_5Cl	1.35*	14	7.05*	14	2.90	0.47	2.43
Benzyl chloride	C_7H_7Cl	1.10	9	———	—	2.40	0.46	———
Dichloroethylene	$C_2H_2Cl_2$	7.00	6	19.50*	6	9.47	0.74	2.06
Ethylene dichloride	$C_2H_4Cl_2$	6.20	46	15.90*	46	7.72	0.80	2.06
Propylene dichloride	$C_3H_6Cl_2$	3.40	47	14.50*	47	4.97	0.68	2.92
Bromides								
Methyl bromide	CH_3Br	13.50	45	14.50	45	12.24	1.10	1.18
Ethyl bromide	C_2H_5Br	6.75	45	11.25	45	6.52	1.04	1.73

*Determinations made at elevated temperatures.

[a]P.C.C. = Per cent combustible in air. Mixture for theoretical complete combustion.

NOTE: See end of table for bibliographic reference notes.

TABLE 1, *Concluded*

Limits of Inflammability of Gases and Vapors in Air

Name	Formula	Limits of inflammability, percentage (by volume). Lower	Ref. No.	Upper	Ref. No.	Percentage by volume combustibles in air. Mixture for theoretical complete combustion	Ratio of lower limit to P.C.C.[a] Column 3 ÷ 5	Ratio of upper limit to P.C.C.[a] Column 4 ÷ 5
(1)	(2)	(3)		(4)		(5)	(6)	(7)
Gases								
Blast furnace gas		35.00	48	73.50	48	——	——	——
Coal gas		6.50	4	36.00	4	——	——	——
Coal gas		5.30	49	33.00	49	——	——	——
Natural gas		4.30	49	13.50	49	——	——	——
Natural gas		4.90	49	15.00	49	——	——	——
Oil gas		4.75	49	32.50	49	——	——	——
Producer gas		20.70	48	73.70	48	——	——	——
Water gas		6.00	2	70.00	2	——	——	——
Petroleum Products								
Gasoline, regular		1.40	6	7.50	6	——	——	——
Gasoline, 73 octane		1.50	6	7.40	6	——	——	——
Gasoline, 92 octane		1.50	6	7.60	6	——	——	——
Gasoline, 100 octane		1.45	6	7.50	6	——	——	——
Naphtha		1.10	9	6.00	9	——	——	——
Organometallic Compounds								
Tetramethyllead	$C_4H_{12}Pb$	1.80	9	——	—	2.72	0.66	——
Tetramethyltin	$C_4H_{12}Sn$	1.90	9	——	—	2.72	0.70	——

*Determinations made at elevated temperatures.
[a]P.C.C. = Per cent combustible in air. Mixture for theoretical complete combustion.

[5] G. W. Jones and R. E. Kennedy, *U.S. Bur. Mines Repts. Investigations* No. **3216** (1933).
[6] G. W. Jones and W. E. Miller, *U.S. Bur. Mines, unpublished results.*
[7] G. W. Jones and R. E. Kennedy, *U.S. Bur. Mines Repts. Investigations* No. **3337** (1937).
[8] M. J. Burgess and R. V. Wheeler, *J. Chem. Soc.*, **99**, 2013 (1911).
[9] Assoc. Factory Mutuals Ins. Cos., *Ind. Eng. Chem.*, **32**, 880 (1940).
[10] H. Le Chatelier and O. Boudouard, *Compt. rend.*, **126**, 1344 (1898).
[11] G. W. Jones, W. P. Yant, W. E. Miller, and R. E. Kennedy, *U.S. Bur. Mines Repts. Investigations* No. **3278** (1935).
[12] G. W. Jones and R. E. Kennedy, *U.S. Bur. Mines Repts. Investigations* No. **3565** (1941).
[13] G. W. Jones and R. E. Kennedy, *U.S. Bur. Mines, unpublished results.*
[14] G. W. Jones, F. E. Scott, and G. S. Scott, *U.S. Bur. Mines, unpublished results.*
[15] A. G. White, *J. Chem. Soc.*, **125**, 2387 (1924).
[16] G. W. Jones, E. S. Baker, and W. E. Miller, *U.S. Bur. Mines. Repts. Investigations* No. **3337** (1937).
[17] A. G. White, *J. Chem. Soc.*, **121**, 1244 (1922).
[18] G. W. Jones, G. S. Scott, and W. E. Miller, *U.S. Bur. Mines Repts. Investigations* No. **3630** (1942).
[19] G. W. Jones, R. E. Kennedy, and G. J. Thomas, *U.S. Bur. Mines Repts., Investigations* No. **3511** (1940).
[20] M. Briand, P. Dumanois, and P. Laffitte, *Compt. rend.*, **197**, 322 (1933).
[21] M. J. Burgess and G. Greenwood, *U.S. Bur. Mines Bull.* No. **279**, 80 (1939).

unusually small apparatus and those in which the direction of flame propagation was other than upward have not been included, except where no other values were available. In some cases values reported by several investigators were found to be in good agreement; however, only one reference has been given. Column (1) gives the name; (2), the formula; (3), the lower limit of inflammability; (4), the upper limit of inflammability; (5), the percentage of combustible required for theoretical complete combustion in air; (6), the ratio of the lower limit of inflammability to the percentage required for theoretical complete combustion; and (7) a similar ratio for the upper limit of inflammability.

C. CALCULATION OF LIMITS OF INFLAMMABILITY

1. *One Combustible*

Burgess and Wheeler[8] first showed that there is a definite relationship between the calorific value of the combustible and its lower limit of inflammability. The calorific values of the pure paraffin hydrocarbons multiplied by their lower limits of inflammability gave a constant; that is, on combustion a lower-limit mixture of any of the paraffin hydrocarbons with air liberates the same amount of heat.

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[22] Y. Nagai, *Proc. Imp. Acad. Tokyo*, **2**, 284 (1926).
[23] A. G. White, *J. Chem. Soc.*, **115**, 1462 (1919).
[24] Louis and Entezam, *Ann. combustibles liquides*, **14**, 21 (1939).
[25] G. W. Jones and J. R. Klick, *Ind. Eng. Chem.*, **21**, 791 (1929).
[26] G. W. Jones and B. B. Beattie, *Ind. Eng. Chem.*, **26**, 557 (1934).
[27] H. Le Chatelier and O. Boudourard, *Bull. soc. chim.*, **19**, 483 (1898).
[28] A. H. Nuckolls, *Underwriters' Lab., Method for the Classification of the Hazards of Liquids*, 1929.
[29] G. W. Jones, W. E. Miller, and H. Seaman, *Ind. Eng. Chem.*, **25**. 694 (1933).
[30] R. V. Wheeler, *U.S. Bur. Mines Bull.* No. **279**, 93 (1939).
[31] G. W. Jones, *U.S. Bur. Mines Tech. Paper* No. **450** (1929).
[32] H. F. Coward and F. Brinsley, *J. Chem. Soc.*, **105**, 1859 (1914).
[33] W. Payman and H. Titman, *Nature*, **137**, 190 (1936).
[34] G. W. Jones and R. E. Kennedy, *Ind. Eng. Chem.*, **22**, 146 (1930).
[35] R. M. Jones, *Ind. Eng. Chem.*, **25**, 394 (1933).
[36] G. W. Jones, H. Seaman, and R. E. Kennedy, *Ind. Eng. Chem.*, **25**, 1283 (1933).
[37] H. H. Franck and G. Doring, *Angew. Chem.*, **44**, 273 (1931).
[38] A. G. White, *J. Chem. Soc.*, **121**, 1688 (1922).
[39] E. Berl and K. Barth, *Elektrochem.*, **39**, 73 (1933).
[40] G. W. Jones, R. E. Kennedy, and G. S. Scott, *U.S. Bur. Mines Repts. Investigations* No. **3597** (1941).
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[42] G. W. Jones, G. S. Scott, and W. E. Miller, *U.S. Bur. Mines Repts. Investigations* No. **3640** (1942).
[43] W. Hempel, *Gasanalytische Methoden*. Braunschweig, 1913.
[44] G. W. Jones, R. E. Kennedy, and W. E. Miller, *U.S. Bur. Mines Repts. Investigations* No. **3648** (1942).
[45] G. W. Jones, *Ind. Eng. Chem.*, **20**, 367 (1928).
[46] G. W. Jones and R. E. Kennedy, *Ind. Eng. Chem.*, **22**, 963 (1930).
[47] G. W. Jones, W. E. Miller, and H. Seaman, *Ind. Eng. Chem.*, **25**, 771 (1933).
[48] A. Grebel, *Mem. et compt. rend. soc. ing. civils (France)*, **83**, 35 (1930).
[49] C. M. Cooper and P. F. Wiezevich, *Ind. Eng. Chem.* **21**, 1210 (1929).

Later Thornton[50] announced that the upper limit bears a direct relation to the amount of oxygen needed for theoretical complete combustion. He stated that for the paraffins the upper-limit mixture contained twice as great a volume of gas as the mixture for theoretical complete combustion; acetylene and carbon disulfide, three times the volume; hydrogen, four times; and carbon monoxide, six times the volume. Lower-limit mixtures that just failed to propagate flame contained twice the volume of oxygen needed for theoretical complete combustion of the paraffin mixtures, and thrice the volume for mixtures of other gases. The values given in columns (6) and (7) of Table 1 show that some of the predictions made by Thornton are approximately correct, while in other cases there are extremely wide variations. The classification is not nearly as simple as Thornton predicted.

If the combustibles are classified according to types, as is done in Table 1, the relationships between the limits and the oxygen required for theoretical complete combustion show better agreement. For the lower limits the average ratio for a given type may be used to predict the limits of compounds for which limits of inflammability have not been determined.

An example showing the application of this method in predicting the limits of inflammability of a new compound will be discussed. Let it be assumed that the lower limit of inflammability of propyl chloride has not been determined and it is desired to predict its lower limit of inflammability. The ratios of the lower limits to those for theoretical complete combustion for the gases to be used in the prediction are given below:

Methane	0.53	Methyl chloride	0.67
Ethane	0.55	Ethyl chloride	0.61
Propane	0.52	Propyl chloride	not known

The addition of one chlorine atom to methane has raised the ratio 0.14, while the addition of one chlorine atom to ethane has raised the ratio only 0.06. One chlorine atom added to propane should raise the ratio even less, say 0.05, thus giving a ratio of 0.57 for propyl chloride. When propyl chloride is burned with the theoretical amount of oxygen to give complete combustion the following reaction takes place:

$$C_3H_7Cl + 4.5\ O_2 = 3\ CO_2 + HCl + 3\ H_2O$$

or with air:

$$C_3H_7Cl + 21.5\ \text{air} = 3\ CO_2 + HCl + 3\ H_2O + 17.0\ N_2$$

The percentage of propyl chloride in a mixture with air to give theoretical complete combustion $= \dfrac{1 \times 100}{22.5} = 4.44$ per cent. Using the ratio 0.57 for propyl chloride estimated above, the predicted lower limit of inflammability $= 4.44 \times 0.57 = 2.53$ per cent. Recently the lower limit of inflammability of this combustible was determined to be 2.60 per cent. This gives a ratio of 0.59 or a difference of 0.02 from the predicted ratio and a difference of 0.07 per cent between the determined and predicted lower limits of inflammability.

[50] W. M. Thornton, *Phil. Mag.*, **33**, 190 (1917).

2. Two or More Combustibles

The calculation of the limits of inflammability of combustible mixtures from a knowledge of the limits of each combustible and the percentage of each combustible present in the mixture can be done rather accurately for a number of mixtures by the application of the so-called "mixture law."

Le Chatelier[10] first applied the law to the limits of inflammability of gases. The law states that if we have separate, limit combustible-air mixtures and mix them, then this mixture will also be a limit mixture. The equation for expressing this law in its simplest useful form is written as follows:

$$L = \frac{100}{\frac{P_1}{N_1} + \frac{P_2}{N_2} + \frac{P_3}{N_3} + \frac{P_4}{N_4}}$$

Where P_1, P_2, P_3, and P_4 are the proportions of the various combustible gases present in the mixture, free of air and inerts, (so that $P_1 + P_2 + P_3 + P_4 = 100$) and N_1, N_2, N_3, and N_4 are the respective lower, or upper, limits of inflammability of the combustibles in air: then L is the lower, or upper, limit of inflammability of the mixture.

As an example of the application of the method we may take a natural gas of the following composition:

Hydrocarbon	Percentage (by volume)	Limits of inflammability, percentage (by volume)	
		Lower	Upper
Methane	80.0	5.00	15.00
Ethane	15.0	3.10	12.50
Propane	4.0	2.10	10.10
Butane	1.0	1.86	8.40

$$\text{Lower limit} = \frac{100}{\frac{80.0}{5.00} + \frac{15.0}{3.10} + \frac{4.0}{2.10} + \frac{1.0}{1.86}} = 4.30$$

$$\text{Upper limit} = \frac{100}{\frac{80.0}{15.00} + \frac{15.0}{12.50} + \frac{4.0}{10.10} + \frac{1.0}{8.40}} = 14.18$$

This law has been tested by Coward, Carpenter, and Payman[1] and proved to hold for hydrogen, carbon monoxide, and methane containing no inert gases in normal air. Subsequent tests made with paraffin hydrocarbons in air[3] showed that the law could also be applied to these mixtures. Exceptions have been found in tests made with some inflammable gases. White[17] found that the law does not hold strictly for hydrogen-ethylene–air mixtures, acetylene–hydrogen–air mixtures,

hydrogen sulfide–methane–air mixtures, and mixtures containing carbon disulfide. In tests on some chlorinated hydrocarbons, Coward and Jones[51] found that the law did not hold for methane–dichloroethylene–air mixtures. Also it was found[45] that it was only approximately correct for mixtures of methyl and ethyl chlorides. It is therefore apparent that the mixture law, useful when its applicability has been proved, cannot be applied indiscriminately, but must first be proved to hold for the combination of gases under investigation.

Many industrial processes require the use of mixtures of various solvents, and although the limits of inflammability of the various individual constituents in the mixture may be known, it is not at all certain what the limits of inflammability will be for the various mixtures. Investigations of the lower limits of inflammability of various solvent mixtures have shown[16] that where the ratios of lower limits of the individual constituents to the amount of oxygen required for theoretical complete combustion are about the same, the limits of mixtures of the constituents may be determined accurately by calculation. For example, mixtures of benzene, furfural, and acetone, which have ratios ranging from 0.50 to 0.53, may have their limits calculated;[25] and mixtures of ethyl acetate, ethyl alcohol, and toluene, whose ratios vary from 0.50 to 0.56, also have been found[16] to give calculated results agreeing closely with experimental results.

To date, the accuracy of the above prediction has been proved only for a limited number of mixtures. As information on the subject is accumulated, the classification of compounds according to the ratios should be of considerable value in predicting and calculating the limits of inflammability of mixtures of combustible gases and vapors.

3. *Complex Gas Mixtures*

It is possible to calculate closely the limits of inflammability not only of mixtures of combustible gases and vapors in air but also mixtures containing varying amounts of inert gases and air. The limits of inflammability of natural, manufactured, producer, blast-furnace, automobile, and sewage gases when mixed with various proportions of the inert gases present may be calculated from a knowledge of the composition of the gas and the inflammability of the various constituents present. The actual procedure is rather long and complicated, and tables or graphs are required for ascertaining the limits of the combustible-inert gas components. The reader who wishes to make such calculations is referred to published reports on the subject.[2, 5, 31, 52]

D. LIMITS OF INFLAMMABILITY OF GASES AND VAPORS IN OXYGEN

In some instances, for example in the compressed-gas industry and in hospitals, the inflammability of combustible gases in oxygen is of real importance. Published information on this phase of the subject is limited and in many cases the values

[51] H. F. Coward and G. W. Jones, *Ind. Eng. Chem.*, **22**, 963 (1930).
[52] J. Yeaw, *Ind. Eng. Chem.*, **21**, 1030 (1929).

appear to be unreliable. A compilation of the best available information on the limits in oxygen is given in Table 2.

TABLE 2

Limits of Inflammability of Gases and Vapors in Oxygen

Name	Formula	Limits of inflammability, percentage (by volume)			
		Lower	Reference	Upper	Reference
Acetylene	C_2H_2	2.80	53	93.00	53
Ammonia	NH_3	14.80	38	79.00	38
Benzene	C_6H_6	2.80	54	29.90	54
Carbon monoxide	CO	15.50	55	93.90	55
Cyclopropane	C_3H_6	2.48	19	60.00	19
Deuterium	De	4.90	33	94.70	33
Diethyl ether	$C_4H_{10}O$	2.10	11	82.00	11
Divinyl ether	C_4H_6O	1.85	26	85.50	26
Ethane	C_2H_6	4.10	54	50.50	56
Ethyl chloride	C_2H_5Cl	4.05	13	67.20	13
Ethylene	C_2H_4	2.90	11	79.90	57
Hydrogen	H_2	4.65	7	93.90	7
Methane	CH_4	5.40	58	58.40	49
Methyl chloride	CH_3Cl	8.20	59	65.80	59
Methylene chloride	CH_2Cl_2	15.50	13	66.40	13
Propylene	C_3H_6	2.10	57	52.80	57
Trichloroethylene	C_2HCl_3	10.30	60	64.50	60

II. Ignition Temperatures

Before an explosive mixture can propagate flame a portion of the mixture must be heated to its ignition temperature. The ignition temperature may be defined as that minimum temperature at which rapid combustion becomes independent of external supplies of heat. This implies that in order to initiate flame a definite minimum volume of the gaseous mixture must be heated to its ignition temperature and held at this temperature for a sufficient time to enable flame to propagate away from the ignition source. The time period at the ignition temperature necessary to cause the propagation of flame varies within wide limits. For a gas such as hydrogen the time period, or so-called "lag," may be only a fraction of a second, while for ethane the time period may be 100 seconds or longer. It is therefore apparent that while the temperature at which a given mixture will ignite and burst into flame is of great importance, the "lag" at the ignition temperature also must be considered, because it often happens that an ignition source may be adequate as far as the temperature is

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concerned, yet the duration is so short that the ignition source is incapable of initiating a self-propagating flame and the mixture fails to ignite.

A. FACTORS AFFECTING IGNITION TEMPERATURE

The investigation of ignition temperatures is extremely complicated, and the results obtained by various investigators may show wide disagreement because of different experimental conditions. Some of the major factors that affect the ignition temperatures are: the percentage of combustible in the mixture, the "lag" or time required at a given temperature to cause ignition, the percentage of oxygen present, the size, shape, and composition of the apparatus used, the pressure on the experimental mixture at the time of ignition, and the presence or absence of impurities and catalysts in the mixture.

On the basis of the above discussion it becomes apparent that the term "ignition temperature" is not a true physical constant and reported values for a given combustible may vary widely.

B. MINIMUM IGNITION TEMPERATURES OF GASES AND VAPORS

The values tabulated in Table 3 may be termed "minimum ignition temperatures of gases and vapors in air." In those instances where numerous values have been reported the lowest apparently reliable one has been taken, after due consideration has been given to the size of the apparatus, the composition of the surface that came into contact with the heated mixture, and the method used to determine the ignition temperatures.

TABLE 3

Minimum Ignition Temperatures and Flash Points of Combustible Liquids, Gases, and Vapors

Name	Formula	Ignition temperatures			Flash points		
		° F.	° C.	Ref. No.	° F.	° C.	Ref. No.
Acetal	$C_6H_{14}O_2$	446	230	6	—	—	—
Acetaldehyde	C_2H_4O	527	275	6	−17	−27	9
Acetanilide	C_8H_9NO	—	—	—	345	174	9
Acetic acid	$C_2H_4O_2$	1022	550	6	107	42	28
Acetic anhydride	$C_4H_6O_3$	738	392	11	127	53	28
Acetone	C_3H_6O	1042	561	29	0	−18	9
Acetophenone	C_8H_8O	—	—	—	221	105	9
Acetyl chloride	C_2H_3OCl	—	—	—	40	4	61
Acetylene	C_2H_2	581	305	62	gas	gas	—
Acrolein	C_3H_4O	532	278	48	—	—	—
Acrylonitrile	C_3H_3N	898	481	40	23	−5	11
Aldol	$C_4H_8O_2$	—	—	—	181	83	9
Allyl alcohol	C_3H_6O	712	378	63	70	21	9
Allyl chloride	C_3H_5Cl	909	487	6	—	—	—
Ammonia	NH_3	1204	651	64	gas	gas	—
Amyl acetate	$C_7H_{14}O_2$	750	399	28	77	25	28
Isoamyl acetate	$C_7H_{14}O_2$	714	379	63	92	33	9
Amyl alcohol	$C_5H_{12}O$	801	427	6	100	38	28
p-Isoamyl alcohol	$C_5H_{12}O$	650	343	28	114	45	28
sec-Isoamyl alcohol	$C_5H_{12}O$	—	—	—	103	39	28

TABLE 3. *Continued*

Name	Formula	Ignition temperatures			Flash points		
		° F.	° C.	Ref. No.	° F.	° C.	Ref. No.
tert-Amyl alcohol	$C_5H_{12}O$	—	—	—	67	19	9
Amylbenzene	$C_{11}H_{16}$	491*	255*	65	—	—	—
Amyl chloride	$C_5H_{11}Cl$	498	259	6	—	—	—
tert-Amyl chloride	$C_5H_{11}Cl$	649	343	6	—	—	—
Amylene	C_5H_{10}	523	273	36	—	—	—
Isoamyl ether	$C_{10}H_{22}O$	802	428	66	—	—	—
Amyl propionate	$C_8H_{16}O_2$	—	—	—	106	41	67
Aniline	C_6H_7N	986	530	68	160	71	65
Anthracene	$C_{14}H_{10}$	882	472	69	—	—	—
Benzaldehyde	C_7H_6O	377	192	28	148	64	28
Benzene	C_6H_6	1076	580	63	12	−11	9
Benzoic acid	$C_7H_6O_2$	1063*	573*	20	250	121	70
Benzyl acetate	$C_9H_{10}O_2$	860	460	63	216	102	9
Benzyl alcohol	C_7H_8O	802	428	63	213	101	9
Benzyl chloride	C_7H_7Cl	1161	627	66	140	60	9
Bromobenzene	C_6H_5Br	1270	688	66	149	65	71
Butadiene	C_4H_6	804	429	6	—	—	—
Butane	C_4H_{10}	826	441	72	gas	gas	—
Isobutane	C_4H_{10}	1010	543	71	gas	gas	—
Dichlorobutane	$C_4H_8Cl_2$	543	284	14	0	−18	14
Butyl acetate	$C_6H_{12}O_2$	790	421	63	84	29	28
Butyl alcohol	$C_4H_{10}O$	653	345	63	100	38	28
Isobutyl alcohol	$C_4H_{10}O$	813	434	63	82	28	71
tert-Butyl alcohol	$C_4H_{10}O$	892	478	6	52	11	6
sec-Butyl alcohol	$C_4H_{10}O$	777	414	6	70	21	14
sec-Butylbenzene	$C_{10}H_{14}$	—	—	—	126	52	73
Butyl bromide	C_4H_9Br	901	483	66	—	—	—
Butylcarbitol	$C_8H_{10}O_3$	442	228	9	172	78	9
Butyl Cellosolve	$C_6H_{14}O_2$	472	244	9	141	61	9
Butyl chloride	C_4H_9Cl	860	460	6	—	—	—
Butylene	C_4H_8	829	443	36	gas	gas	—
Butyl formate	$C_5H_{10}O_2$	635	335	14	64	18	71
Butyl propionate	$C_7H_{14}O_2$	799	426	63	90	32	9
Butyraldehyde	C_4H_8O	446	230	14	20	−7	9
Butyric acid	$C_4H_8O_2$	1026	552	66	170	77	9
Carbon disulfide	CS_2	248	120	74	−22	−30	28
Carbon monoxide	CO	1128	609	75	gas	gas	—
Cellosolve	$C_4H_{10}O_2$	460	238	9	104	40	9
Cellosolve acetate	$C_6H_{12}O_3$	715	379	9	124	51	9
Chlorobenzene	C_6H_5Cl	—	—	—	85	29	76
Chloroethyl acetate	$C_4H_7O_2Cl$	—	—	—	129	54	9
Creosote	———	637	356	9	165	74	9
o-Cresol	C_7H_8O	1110	599	66	178	81	71
m-Cresol	C_7H_8O	1159	626	66	187	86	71
Crotonaldehyde	C_4H_6O	450	232	36	55	13	9
Cyanamide	CN_2H_2	—	—	—	285	141	9
Cyanogen	C_2N_2	1562	850	77	gas	gas	—
Cyclohexane	C_6H_{12}	565	296	65	1	−17	71
Cyclohexanol	$C_6H_{12}O$	—	—	—	154	68	78
Cyclohexanone	C_6H_8O	—	—	—	93	34	9
Cyclopropane	C_3H_6	928	498	6	gas	gas	—
Cymene	$C_{10}H_{14}$	871	466	66	117	47	9
Decalin	$C_{10}H_{18}$	504	262	9	136	58	78
Decane	$C_{10}H_{22}$	482	250	79	115	46	9
Dichloroethyl ether	$C_4H_8OCl_2$	696	369	9	131	55	9

*Determinations made in oxygen.

TABLE 3, *Continued*

Minimum Ignition Temperatures and Flash Points of Combustible Liquids, Gases, and Vapors

Name	Formula	Ignition temperatures			Flash points		
		° F.	° C.	Ref. No.	° F.	° C.	Ref. No.
Dichloroethylene	$C_2H_2Cl_2$	856	441	6	57	14	9
Diethanolamine	$C_4H_{11}NO_2$	1224	662	9	280	138	9
Diethylene glycol	$C_4H_{10}O_3$	775	413	63	255	124	9
Dimethylaniline	$C_8H_{11}N$	700	371	9	145	63	9
Dioxane	$C_4H_8O_2$	511	266	36	54	12	80
Diphenyl	$C_{12}H_{10}$	—	—	—	235	113	9
Diphenylamine	$C_{12}H_{11}N$	—	—	—	307	153	9
Diphenylmethane	$C_{13}H_{12}$	—	—	—	266	130	9
Diphenyloxide	$C_{12}H_{10}O$	—	—	—	239	115	9
Divinyl ether	C_4H_6O	680	360	26	−22	−30	9
Dodecane	$C_{12}H_{26}$	993	534	66	165	74	9
Ethane	C_2H_6	882	472	3	gas	gas	—
Ethyl acetate	C_4H_8O	903	484	63	28	−2	28
Ethyl alcohol	C_2H_6O	738	392	81	54	12	28
Ethylbenzene	C_8H_{10}	1027	553	66	59	15	9
Ethyl bromide	C_2H_5Br	952	511	64	—	—	—
Ethyl butyrate	$C_6H_{12}O_2$	865	463	6	78	26	9
Ethyl chloride	C_2H_5Cl	963	517	6	−58	−50	9
Ethylene	C_2H_4	914	490	82	gas	gas	—
Ethylenechlorohydrin	C_2H_5OCl	797	425	6	140	60	9
Ethylene dichloride	$C_2H_4Cl_2$	775	413	9	56	13	9
Ethylene glycol	$C_2H_6O_2$	775	413	9	232	111	9
Ethylene oxide	C_2H_4O	804	429	9	gas	gas	—
Ethyl ether	$C_4H_{10}O$	379	193	63	−49	−45	83
Ethyl formate	C_3H_6O	1071	577	66	−4	−20	9
Ethyl mercaptan	C_2H_6S	570	299	44	—	—	—
Ethyl propionate	$C_5H_{10}O_2$	889	476	6	54	12	73
Furfural	$C_5H_4O_2$	736	391	6	140	60	9
Gasoline, regular	———	536	280	64	−47	−44	6
Gasoline, 73 octane	———	570	299	6	—	—	—
Gasoline, 92 octane	———	734	390	6	—	—	—
Gasoline, 100 octane	———	804	429	6	—	—	—
Glycerin	$C_3H_8O_3$	739	393	63	320	160	9
Heptane	C_7H_{16}	451	233	63	25	−4	9
Hexane	C_6H_{14}	478	248	63	−15	−26	28
Isohexane	C_6H_{14}	543	284	65	—	—	—
Hexyl alcohol	$C_6H_{14}O$	572	300	65	137	58	9
Hydrocyanic acid	HCN	1000	538	9	gas	gas	—
Hydrogen	H_2	1065	574	84	gas	gas	—
Hydrogen sulfide	H_2S	558	292	85	gas	gas	—
Isoprene	C_5H_8	824	440	86	—	—	—
Kerosene	———	491	255	71	100–165	38–74	9
Methane	CH_4	1170	632	87	gas	gas	—
Methyl acetate	$C_3H_6O_2$	936	502	63	14	−10	28
Methyl alcohol	CH_4O	878	470	63	52	11	65
Methyl bromide	CH_3Br	999	537	64	—	—	—
Methyl butyl ketone	$C_6H_{12}O$	991	533	36	95	35	9
Methyl butyrate	$C_5H_{10}O_2$	—	—	—	57	14	71
Methyl Cellosolve	$C_3H_8O_2$	551	288	9	107	42	9
Methyl chloride	CH_3Cl	1170	632	88	gas	gas	—
Methylcyclohexane	C_7H_{14}	545	285	65	25	−4	9
Methylcyclohexanol	$C_7H_{14}O$	—	—	—	154	68	9
Methylcyclopentane	C_6H_{12}	624	329	65	—	—	—
Methylene chloride	CH_2Cl_2	1224	662	64	—	—	—
Methyl ethyl ketone	C_4H_8O	957	514	36	30	−1	9

TABLE 3, *Continued*

Name	Formula	Ignition temperatures			Flash Points		
		° F.	° C.	Ref. No.	° F.	° C.	Ref. No.
Methyl formate	$C_2H_4O_2$	456	236	64	−2	−19	9
Methyl propyl ketone	$C_5H_{10}O$	941	505	36	60	16	9
Methyl salicylate	$C_8H_8O_3$	850	454	28	219	104	28
Naphtha	——	450–531	232–277	9	20–110	−7–43	9
Napthalene	$C_{10}H_8$	1038	559	80	176	80	80
Nicotine	$C_{10}H_{14}N_2$	471	244	42	—	—	—
Nitrobenzene	$C_6H_5NO_2$	900	482	28	198	92	28
Nonane	C_9H_{20}	545	285	79	88	31	9
Octane	C_8H_{18}	446	230	79	56	13	9
Oil, cable insulating	——	738	392	14	—	—	—
Oil, castor	——	840	449	9	445	229	9
Oil, cocoanut	——	—	—	—	420	216	9
Oil, cod liver	——	662*	350*	48	—	—	—
Oil, corn	——	—	—	—	490	254	9
Oil, cottonseed	——	650	343	37	486	252	28
Oil, creosote	——	637	336	61	165	74	9
Oil, fish	——	531*	277*	48	420	216	9
Oil, flax	——	772*	411*	48	—	—	—
Oil, gas	——	640	338	9	150	66	9
Oil, lard	——	650	343	28	363	184	28
Oil, linseed, raw	——	650	343	28	432	222	28
Oil, linseed, boiled	——	650	343	28	403	206	28
Oil, lubricating	——	711	377	89	—	—	—
Oil, lubricating, cylinder	——	783	417	9	535	279	9
Oil, lubricating, spindle	——	778	414	71	169	76	9
Oil, lubricating, turbine	——	700	371	9	400	204	9
Oil, menhaden	——	828	442	9	435	224	9
Oil, mineral seal	——	—	—	—	170	77	9
Oil, neat's foot	——	828	442	9	470	243	71
Oil, olive	——	650	343	28	437	225	28
Oil, palm	——	600	315	28	323	162	28
Oil, paraffin	——	—	—	—	444	229	28
Oil, peanut	——	833	445	9	540	282	9
Oil, pine	——	—	—	—	172	78	9
Oil, pine tar	——	—	—	—	144	62	9
Oil, rape	——	836	447	9	464	240	71
Oil, rosin	——	648	342	9	266	130	9
Oil, signal	——	—	—	—	200	93	9
Oil, soybean	——	—	—	—	540	282	9
Oil, sperm	——	586	308	71	428	220	71
Oil, straw	——	—	—	—	315	157	71
Oil, tallow	——	—	—	—	492	256	9
Oil, transformer	——	—	—	—	295	146	9
Oil, tung	——	855	457	9	552	289	9
Oil, Turkey red	——	833	445	9	476	247	9
Oil, whale	——	878	470	90	476	246	71
Paraffin	——	473	245	9	390	199	9
Paraldehyde	$C_6H_{12}O_3$	460	238	9	63	17	9
Pentane	C_5H_{12}	527	275	65	−40	−40	9
Petroleum ether	——	624	329	28	−69	−56	9
Phenol	C_6H_6O	1319	715	9	175	79	73
Pinene	$C_{10}H_{16}$	527	275	65	—	—	—
Propane	C_3H_8	898	481	72	gas	gas	—
Propyl acetate	$C_5H_{10}O_2$	—	—	—	58	14	71
Isopropyl acetate	$C_5H_{10}O_2$	860	460	63	40	4	71

*Determinations made in oxygen.

TABLE 3, *Concluded*

Minimum Ignition Temperatures and Flash Points of Combustible Liquids, Gases, and Vapors

Name	Formula	Ignition temperatures			Flash points		
		° F.	° C.	Ref. No.	° F.	° C.	Ref. No.
Propyl alcohol	C_3H_8O	822	439	6	59	15	9
Isopropyl alcohol	C_3H_8O	853	456	63	53	12	71
Propylbenzene	C_9H_{12}	—	—	—	87	31	71
Isopropylbenzene	C_9H_{12}	—	—	—	102	39	9
Propyl bromide	C_3H_7Br	914	490	6	—	—	—
Propyl chloride	C_3H_7Cl	968	520	6	—	—	—
Propylene	C_3H_6	856	458	36	gas	gas	—
Propylenechlorohydrin	C_3H_7OCl	—	—	—	125	52	9
Propylene dichloride	$C_3H_6Cl_2$	1035	557	36	60	16	36
Propyl ether	$C_6H_{14}O$	372	189	91	—	—	—
Isopropyl ether	$C_6H_{14}O$	830	443	9	−18	−28	9
Propylene oxide	C_3H_6O	—	—	—	−20	−29	9
Propyl formate	C_4H_8O	—	—	—	27	−3	71
Isopropyl formate	C_4H_8O	—	—	—	22	−6	71
Propylene glycol	$C_4H_8O_2$	790	421	14	207	97	14
Pyridine	C_5H_5N	900	482	28	74	23	28
Stearic acid	$C_{18}H_{36}O_2$	743	395	9	385	196	9
Styrene	C_8H_8	914	490	6	86	30	14
Tetradecane	$C_{14}H_{30}$	—	—	—	212	100	9
o-Toluidine	C_7H_9N	900	482	28	202	94	28
p-Toluidine	C_7H_9N	900	482	9	188	87	9
Toluene	C_7H_8	1026	552	63	40	4	9
Trichloroethylene	C_2HCl_3	865	463	6	—	—	—
Triethylene glycol	$C_6H_{14}O_4$	700	371	14	313	156	14
Trimethylbenzene	C_9H_{12}	948	509	65	—	—	—
Turpentine	$C_{10}H_{16}$	464	240	83	95	35	9
Valeric acid	$C_5H_{10}O_2$	1274	690	92	—	—	—
Vinyl ether	C_4H_6O	680	360	36	—	—	—
Vinyl acetate	$C_4H_6O_2$	800	427	9	18	−8	9
o-Xylene	C_8H_{10}	925	496	63	63	17	9
o-Xylidine	$C_8H_{11}N$	—	—	—	206	97	9

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TABLE 4

Ignition Temperatures of Combustible Gases and Vapors in Air and Oxygen

Name	Formula	Minimum ignition temperatures					
		In air			In oxygen		
		° F.	° C.	Ref. No.	° F.	° C.	Ref. No.
Acetal	$C_6H_{14}O_2$	446	230	6	345	174	6
Acetaldehyde	C_2H_4O	527	275	6	318	159	6
Acetic acid	$C_2H_4O_2$	1022	550	6	914	490	6
Acetic anhydride	$C_4H_6O_3$	738	392	14	682	361	14
Acetone	C_3H_6O	1042	561	29	905	485	6
Acetylene	C_2H_2	581	305	62	567	297	62
Acrylonitrile	C_3H_3N	898	481	40	860	460	40
Allyl alcohol	C_3H_6O	712	378	63	658	348	6
tert-Amyl chloride	$C_5H_{11}Cl$	649	343	6	604	318	6
Benzyl alcohol	C_7H_8O	802	428	63	703	373	65
Butyl alcohol	$C_4H_{10}O$	653	345	63	622	328	65
Isobutyl alcohol	$C_4H_{10}O$	813	434	63	687	364	93
tert-butyl alcohol	$C_4H_{10}O$	892	478	6	860	460	6
sec-Butyl alcohol	$C_4H_{10}O$	777	414	6	711	377	6
Butylene chloride	C_4H_7Cl	543	284	14	498	259	11
Butyl formate	$C_5H_{10}O_2$	635	335	14	552	289	11
Butyraldehyde	C_4H_8O	446	230	14	403	206	11
Carbon disulfide	CS_2	248	120	74	225	107	74
Carbon monoxide	CO	1128	609	75	1090	588	75
Cyclopropane	C_3H_6	928	498	6	849	454	6
Ethyl butyrate	$C_6H_{12}O_2$	865	463	6	664	351	6
Ethyl chloride	C_2H_5Cl	963	517	6	874	468	6
Ethylene	C_2H_4	914	490	82	905	485	82
Ethyl ether	$C_4H_{10}O$	379	193	63	360	182	82
Ethyl mercaptan	C_2H_6S	570	299	44	502	261	44
Ethyl propionate	$C_5H_{10}O_2$	889	476	6	824	440	6
Furfural	$C_5H_4O_2$	736	391	6	687	364	6
Glycerin	$C_3H_8O_3$	739	393	63	608	320	9
Methylene chloride	CH_2Cl_2	1188	642	14	1123	606	14
Nicotine	$C_{10}H_{14}N_2$	471	244	42	455	235	42
Propylene glycol	$C_3H_8O_2$	790	421	14	738	392	14
Styrene	C_8H_8	914	490	6	842	450	6

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[86] C. Zerbe and F. Eckert, *Angew. Chem.*, **45**, 593 (1932).
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[91] J. Baron and P. Laffitte, *Compt. rend.*, **206**, 1386 (1938).
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C. IGNITION TEMPERATURES IN AIR AND OXYGEN

From an industrial standpoint the minimum ignition temperatures of combustibles in air are what is desired, although occasionally their ignition temperatures in pure oxygen are desired. It is also of interest to compare the ignition temperatures of combustibles in both air and oxygen, since numerous references dealing with ignition temperatures have reported results in which the ignition temperatures in oxygen were sometimes higher than in air. Such reported results appear very unusual because combustibles heated in pure oxygen to reaction temperatures should react and oxidize at a higher rate and therefore ignite at a lower temperature in oxygen than in air.

The results given in Table 4, which were carried out under similar conditions, prove rather conclusively that combustibles have lower ignition temperatures in oxygen than in air.

III. Flash Points

The flash point may be defined as the minimum temperature at which a liquid gives off vapor sufficient to form an inflammable mixture in contact with air. It is a rather rough yet quick way of measuring the relative combustibility of volatile liquids and, in turn, determines the approximate temperature below which combustibles may be stored and used without creating explosive atmospheres.

In general, the higher the flash point of a liquid, the greater its safety in respect to fires and explosions. It should be emphasized, however, that the flash point alone is not the only measure of the fire and explosion hazards. Other important factors, such as its minimum ignition temperature, inflammable limits, temperature range of inflammability, density of the vapor, and chemical stability are also of marked importance.

The flash point is determined by "closed"- or "open"-cup methods. In either case a given volume of the liquid is heated in a container at a definite rate, and periodically a test flame or spark is passed across the surface of the liquid. The temperature at which, on ignition, a flame passes across the surface of the liquid in the container is taken as the flash point. The container is open to the air in the open-cup method, while in the closed-cup method the space above the liquid is covered. A small opening is uncovered only at the time the test flame is introduced. Lower values are obtained by the closed-cup method and it gives more accurate indications of inflammable-vapor hazards for a given temperature. The flash points tabulated in Table 3 are for the closed-cup method.

IV. Temperature Range of Inflammability

Combustible gases such as methane, hydrogen, and acetylene, when mixed with air in explosive proportions, are but slightly affected as to explosion hazards by moderate changes in temperature. With combustible liquids, a small change in temperature may cause a marked difference as to their explosion hazards. This is especially important for combustible liquids having vapor pressures such as to give

inflammable vapor–air mixtures at or near ordinary room temperatures. The vapor pressure of a liquid may be such that at, say 80° F., its vapor pressure is too low to give inflammable mixtures with air, yet when heated above this temperature a few degrees it will liberate sufficient vapor to create inflammable mixtures.

The United States Bureau of Mines has designed and uses an apparatus, shown in Figure 1, that determines the temperature range over which a given combustible liquid is able to give inflammable mixtures in air saturated with the combustible vapor.

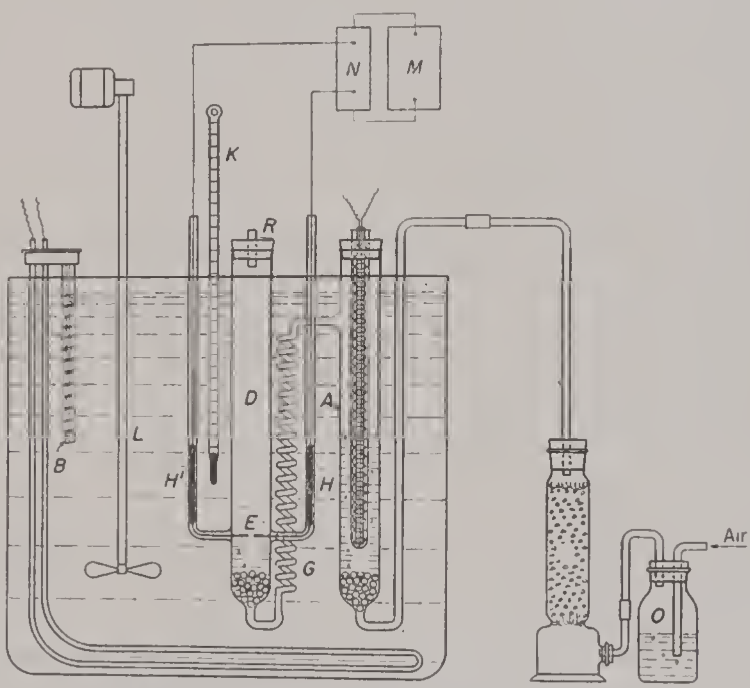

FIG. 1. Apparatus for determining the temperature range of inflammability of combustible liquids.

Explosion tube D is 2.5 cm. in diameter and 20 cm. in length. Platinum electrodes E are employed to ignite the mixtures. Sparks generated by transformer M and induction coil N are passed across electrodes E when a test for explosibility of the atmosphere in the tube is desired. H and H' are mercury seals through which contacts are made between the electrodes and induction coil N. The explosion tube D is immersed in a liquid bath (alcohol, water, or mineral seal oil depending on the temperature required), kept at a uniform temperature by stirrer L, and heated to a desired temperature by an electric heater B. A thermometer K is employed for indicating the temperature of the bath.

To determine the temperature range over which a combustible liquid gives inflammable mixtures, the combustible liquid is poured into D until the level is 2 cm. below the electrodes; cork R which has an opening in its center, is placed in the top

of explosion tube D. Air is turned on and adjusted to flow at the rate of 2 liters per hour, as indicated by bubbler A. The air then passes through a tower containing a drying agent, and thence through glass coil G in the bath to bring the air to the temperature of the bath, before it passes through the combustible liquid into explosion tube D. Air is passed through the liquid at the above rate for 10 minutes at a given temperature, and then a test for inflammability is made by loosening cork R and causing sparks to pass across electrodes E. If the combustible liquid gives an inflammable mixture with air at the temperature tested, flame will pass up the tube and out the top. Tests are continued by the method of trial and error until a minimum temperature is obtained at which flame carries from the electrodes upward through the tube. The temperature of the bath is then raised, and the temperature at which the upper limit is reached is ascertained in a similar manner.

From a practical standpoint, the temperature range of inflammability means that if the combustible liquid is stored or used at temperatures below the minimum given above, inflammable mixtures with air cannot be obtained. However, as soon as the minimum temperature is exceeded, inflammable mixtures are created if air is saturated with the combustible vapor liberated by the liquid and such saturated air continues to be inflammable until the upper temperature value is reached. At this temperature the percentage of vapor in air saturated with the vapor liberated by the liquid becomes so high that the mixture is incapable of propagating flame. It should be noted that mixtures of air saturated with vapor at the upper temperature limit or higher, although not inflammable per se, do become inflammable when additional air is added.

The temperature range of inflammability for typical combustible liquids is given in Table 5. The flash points also are given so that comparison may be made with the lower temperature limit.

In the tests made in the apparatus shown in Figure 1, flame is propagated upward, and the vapor-air mixture is maintained at the same temperature as the combustible liquid. Under these conditions lower temperatures should be obtained than those in standard closed-cup flash-point testing apparatus, since in the latter the vapor is not uniformly mixed with the air at the time of ignition, the mixture is ignited from above so that the propagating flame travels horizontally and downward, and for combustible liquids having flash points above normal room temperature the vapor-air mixture is at a lower temperature than that of the liquid. These factors tend to give flash points some degrees higher than the minimum temperature at which the liquid may liberate combustible vapor in amounts sufficient to create inflammable mixtures in contact with air.

The fact that the flash points of all the combustible liquids listed in Table 5 are higher than the minimum temperature of inflammability bears out this conclusion. In some cases the difference amounts to 15 to 20° F. and in others somewhat less. The practical significance of these results is that the flash point does not give the absolute minimum temperature at which inflammable mixtures may be produced. To be sure that the liquid will not create inflammable atmospheres in contact with

TABLE 5

Temperature Range of Inflammability and Flash Points of Typical Combustible Liquids

Name	Formula	Boiling point ° C.	Flash point		Temperature range of inflammability			
					Lower		Upper	
			° F.	° C.	° F.	° C.	° F.	° C.
Acetone	C_3H_6O	56.5	0	−18	−4	−20.0	41	5.0
Acetic acid	$C_2H_4O_2$	118.1	108	42	99	37.3	136	57.9
Acrylonitrile	C_3H_3N	76.0	23	−5	21	−6.2	85	29.4
Isoamyl acetate	$C_7H_{14}O_2$	142.0	91	33	79	26.5	140	60.0
Allyl alcohol	C_3H_6O	96.6	70	21	66	19.0	138	58.8
Amyl chloride	$C_5H_{11}Cl$	106.6	—	—	42	5.5	104	40.0
Butyl iodide	C_4H_9I	129.6	—	—	92	33.5	126	52.0
Chlorobutene	C_4H_7Cl	67.0	0	−18	−9	−23.0	40	4.5
Crotonaldehyde	C_4H_6O	104.0	55	13	47	8.5	113	45.0
Dioxane	$C_4H_8O_2$	101.0	54	12	47	8.5	137	58.5
Ethylene dichloride	$C_2H_4Cl_2$	84.0	55	13	52	11.0	93	34.0
Furfural	$C_5H_4O_2$	161.0	140	60	133	56.0	237	114.0
Methyl alcohol	CH_4O	66.0	52	11	46	8.0	99	37.0
Methyl Cellosolve	$C_3H_8O_2$	124.5	108	42	93	34.0	176	80.0
Methyl butyl ketone	$C_6H_{12}O$	127.0	95	35	72	22.5	139	59.5
Naphtha	———	Variable	101	38	98	37.0	163	72.8
Propylene dichloride	$C_3H_6Cl_2$	96.8	61	16	52	11.0	97	36.0
Propylene glycol	$C_3H_8O_2$	188.0	207	97	205	96.0	266	130.0

air, a temperature varying from 5 to 20° F. below the flash point must not be exceeded.

V. Methods of Minimizing Explosions

A. CONTROL OF THE OXYGEN CONTENT OF THE ATMOSPHERE

The fact that no combustible gas, vapor, mist, or pulverized solid will burn or explode when the oxygen content of the atmosphere is reduced below a certain definite value, which is specific for the combustible material under consideration, enables one definitely to control and in many cases actually to eliminate explosion hazards.

The oxygen present in an explosive atmosphere may be reduced by direct absorption, using special reagents and catalysts, or by dilution with inert gases such as nitrogen, carbon dioxide, or combinations of these inerts as represented by flue gas or exhaust gas from internal-combustion engines. Automobile exhaust gas and flue gases made by burning fuel gas or fuel oil with the proper proportions of air have low oxygen contents and are especially suited for reducing the oxygen content of atmospheres. Carbon dioxide compressed in cylinders or stored in the liquid state in special holders maintained at low temperatures, dry ice, carbon tetrachloride, and the Freons (halogenated methane compounds) may be used also for this purpose. It should be remembered that no toxic gas or vapor is suitable for use as a diluent in situations where it may be inhaled; likewise atmospheres deficient in oxygen may not be respirable.

Table 6 shows for a number of combustible gases and vapors the critical oxygen values, below which flames will not propagate or explosions take place when the reduction of the oxygen content is brought about by the addition of nitrogen and the addition of carbon dioxide. The critical oxygen values for any given combustible vary with the concentration of the combustible present; however, the values given in Table 6 are minimum ones and cover any concentrations of the combustible that may be present.

TABLE 6

Oxygen Values below Which Flames of Combustible Gases and Vapors Are Extinguished

Name	Formula	Oxygen percentage below which no mixture is inflammable			
		Nitrogen as diluent in air	Ref. No.	Carbon dioxide as diluent in air	Ref. No.
Methane	CH_4	12.1	94	14.6	94
Ethane	C_2H_6	11.0	95	13.4	95
Propane	C_3H_8	11.4	5	14.3	5
Butane	C_4H_{10}	12.1	5	14.5	5
Pentane	C_5H_{12}	12.1	96	14.4	96
Hexane	C_6H_{14}	11.9	96	14.5	96
Ethylene	C_2H_4	10.0	57	11.7	57
Propylene	C_3H_6	11.5	97	14.1	97
Cyclopropane	C_3H_6	11.7	19	13.9	19
Acetone	C_3H_6O	13.5	98	15.6	98
Butadiene	C_4H_6	10.5	99	13.1	99
Carbon disulfide	CS_2	——	—	8.0	100
Carbon monoxide	CO	5.6	101	5.9	101
Ethyl ether	$C_4H_{10}O$	——	—	13.0	100
Gasoline	——	——	—	15.0	100
Hydrogen	H_2	5.0	101	5.9	101
Kerosene	——	——	—	15.0	100
Natural gas	——	12.0	99	14.4	99
Methyl alcohol	CH_4O	10.3	98	13.5	98
Methylene chloride	CH_2Cl_2	18.9	13	——	—

The relationship between concentration of combustible and the critical oxygen requirements to prevent flame propagation is shown to better advantage by preparing graphs, of which an example is given in Figure 2. This graph shows the inflammable areas of all possible mixtures of butadiene, air, and added nitrogen or carbon dioxide. The straight line *ad* represents the composition of mixtures of butadiene and pure air containing up to 18 per cent of butadiene. The inflammable limits, shown by the intercept *bc* on this line, are 2.00 per cent for the lower and 11.50 per

[94] H. F. Coward and F. J. Hartwell, *J. Chem. Soc.*, **129**, 1522 (1926).
[95] G. W. Jones and R. E. Kennedy, *U.S. Bur. Mines Repts. Investigations* No. 3172 (1932).
[96] G. W. Jones and R. E. Kennedy, *Ind. Eng. Chem.*, **27**, 1344 (1935).
[97] G. W. Jones and R. E. Kennedy, *U.S. Bur. Mines Repts. Investigations* No. 3395 (1938).
[98] H. Crouch and E. K. Carver, *Ind. Eng. Chem.*, **17**, 641 (1925).
[99] G. W. Jones and R. E. Kennedy, *U.S. Bur. Mines Repts. Investigations* No. 3691 (1943).
[100] National Fire Code for the Prevention of Dust Explosions. Natl. Fire Protect. Assoc. 116 (1943).
[101] G. W. Jones and G. St. J. Perrott, *Ind. Eng. Chem.*, **19**, 985 (1927).

cent for the upper limit. All mixtures between these limits are inflammable. As nitrogen or carbon dioxide is added the oxygen concentration is lowered and, as shown, the limits are narrowed. Finally when the oxygen content is reduced to 10.5 per cent all mixtures of butadiene, air, and added nitrogen become noninflammable. The mixture that will propagate flame with a minimum concentration of oxygen

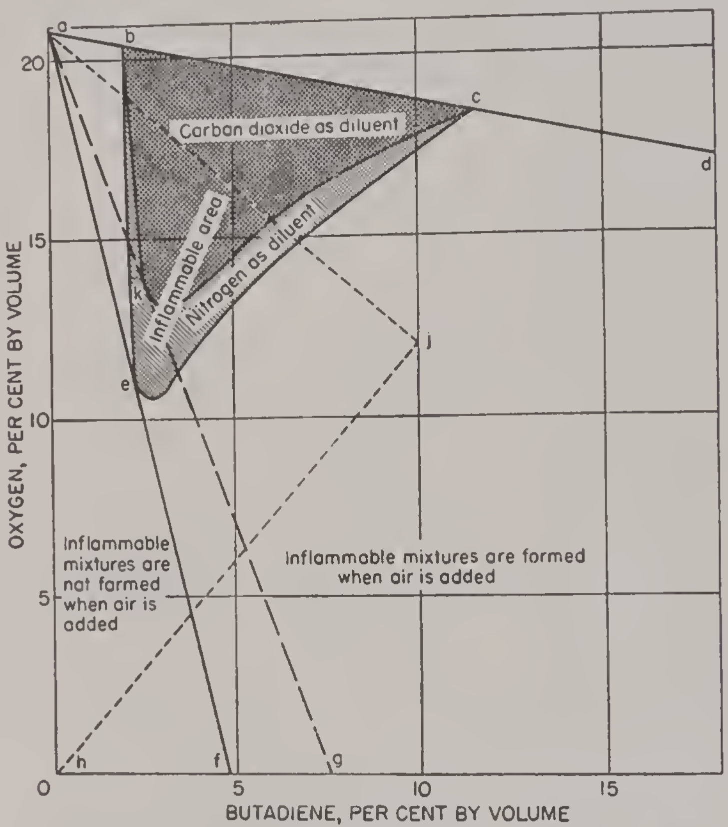

FIG. 2. Inflammability of butadiene, air and added nitrogen, and carbon dioxide.

contains 2.60 per cent of butadiene. If the atmosphere contains 5.00 per cent of butadiene the graph shows that the oxygen concentration needs to be reduced only to 13.2 per cent. Although this mixture having 5.00 per cent butadiene will not propagate flame when the oxygen content is below 13.2 per cent, the graph shows that if air is added to the mixture it becomes inflammable since addition of air shifts the composition of the mixture to the left and toward the point *a* so that the composition passes through a range of mixtures that are inflammable.

The usual problem in dealing with combustible mixtures is to control the atmosphere so that the composition at all times is outside the inflammable range. An example showing how this may be accomplished is given for butadiene, air, and added nitrogen mixtures. The graph, Figure 2, enables one to determine at a glance

the explosion hazards involved. If a particular atmosphere is analyzed and is found to contain, say, 12 per cent of oxygen and 10 per cent of butadiene, as indicated by the point *j* on the graph, this shows at once that the mixture cannot propagate flame until air is added. However, if equipment containing this particular mixture is to be taken out of service and it is desired to do so without the possibilities of explosions, the atmosphere must be altered so as to pass around the inflammable area. It becomes necessary to alter the composition of the atmosphere until it falls into the area left of line *aef*, and in no case should it fall into the inflammable area *bec*. The oxygen content must be reduced to some value below 10.5 per cent to pass safely from the composition given by the point *j* to atmospheres of the composition given by any point to the left of the line *aef*. Nitrogen can be added until the oxygen content is reduced to less than 4.6 per cent, thus shifting the composition along line *jh* and reducing the butadiene content to 3.7 per cent or less; and so a mixture will be obtained that falls into the area left of the line *aef*. The composition of the atmosphere now is such that it cannot be rendered inflammable when air is added, because a line drawn from any point in this area to *a* will not pass through the inflammable area. Air can therefore be added to the equipment and the combustibles swept out without danger of explosions. The graph given in Figure 2 applies only for butadiene. Similar graphs must be constructed for each inflammable concerned.

B. OPERATING OUTSIDE THE RANGE OF INFLAMMABILITY

Processes that necessitate the use of combustible gases or vapors should be carried out, wherever possible, under conditions in which the atmospheres are outside the range of inflammability of the combustibles used. If possible, the concentrations of combustibles should be kept below their lower limit of inflammability, because under these conditions there is no danger of explosions if air finds its way into the mixture. If the concentration of combustibles must be above the lower limit of inflammability, it is advisable to raise the concentration until the combustibles present are above the upper limit. No explosion hazard will result while the atmosphere is above the upper limit; the danger arises only when additional air finds its way into the mixture, and this is most likely to occur when the process is started up or closed down.

When combustible liquids are used, the explosion hazards may be controlled by regulation of the temperature so that the vapor pressure will give atmospheres outside the limits of inflammability. In applying this method of control, the limits of inflammability of the vapor in air, and the vapor pressures of the combustible over the temperature range to be used, must be known; or, by employing the apparatus shown in Figure 1, the temperature range of inflammability may be determined directly.

An example of the application of this method in connection with a solvent naphtha is shown graphically in Figure 3. The graph shows the vapor pressures of the solvent naphtha at various temperatures. The lower and upper temperature limits of inflammability of saturated air mixtures are shown by the points where the

vapor pressure curve crosses the two horizontal lines. The space between the two horizontal lines gives the range of vapor pressures that produce inflammable mixtures when air is saturated with the vapor. The temperature range for this particular naphtha was found to be 98 to 164° F. The graph shows that the naphtha does not have sufficient vapor pressure to create inflammable mixtures with air below 98° F. Above this temperature, inflammable mixtures are produced and continue so until 164° F. is reached, when the combustible vapor content of the saturated-air mixtures

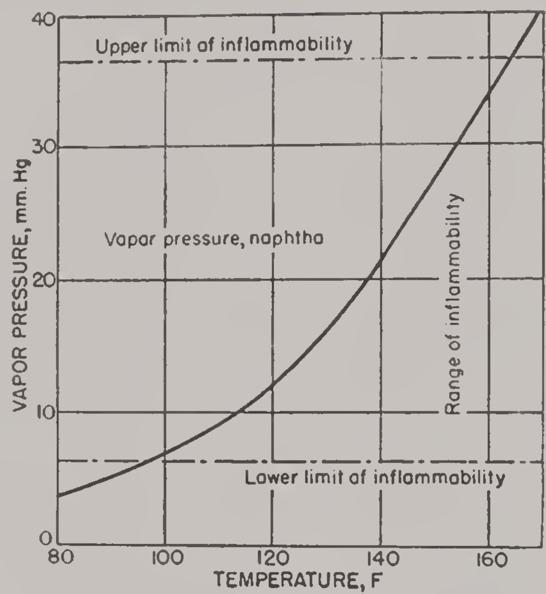

FIG. 3. Relationship between limits of inflammability and vapor pressure of a combustible liquid.

is so high that flame will no longer propagate through the mixture. It should be noted that combustion could take place above 164° F. if the air were not saturated. The graph shows that although the naphtha is relatively safe to use at ordinary room temperatures, a slight increase in temperature renders the combustible highly inflammable in contact with air.

C. USE OF LESS INFLAMMABLE MATERIALS

Wherever possible, combustible liquids with the least inflammable characteristies should be employed. Materials should be used that have vapor pressures at the temperature used that give atmospheres not inflammable in contact with air. When this cannot be done the use of chlorinated hydrocarbons should be considered. The degree of inflammability of a hydrocarbon is reduced by replacing with halogens one or more of the hydrogen atoms in the compound. Table 7 shows how the inflammability of a combustible gas is reduced by successively replacing with chlorine the hydrogen atoms.

TABLE 7

Effect on the Inflammability after Substitution of Chlorine Atoms for Hydrogen in Methane

Name	Formula	Inflammability	Limits of inflammability, percentage (by volume)	
			Lower	Upper
Methane	CH_4	Highly inflammable	5.00	15.00
Methyl chloride	CH_3Cl	Moderately inflammable	8.20	18.70
Methylene chloride	CH_2Cl_2	Not inflammable in air at ordinary temperatures		
Chloroform	$CHCl_3$	Not inflammable in air or oxygen		
Carbon tetrachloride	CCl_4	Not inflammable in air or oxygen		

Methane is highly inflammable in air when the concentrations are within the limits given above. Methyl chloride does not produce as violent explosions as certain methane–air mixtures, yet explosions of this combustible in air may do considerable damage. Methylene chloride is entirely safe when mixed with air at ordinary temperatures and pressures, but it is inflammable in air at elevated temperatures, and when mixed with pure oxygen in the right proportions forms highly explosive mixtures. Chloroform has no explosive properties, while carbon tetrachloride is entirely noninflammable with air or oxygen in any proportions or temperatures, and, in fact, is used to good advantage in the preparation of incombustible, noninflammable dry-cleaning compounds. By the addition of the proper proportions of carbon tetrachloride to combustible liquids, such as naphtha and petroleum distillates, the resulting mixtures are rendered incombustible and noninflammable. However, when these liquid mixtures evaporate, unless the vapor pressure of the combustible portion is as great as that of carbon tetrachloride, inflammable liquid mixtures may remain. At least one serious explosion is known to have occurred from such a mixture. Conversely, should the combustible portion have a vapor pressure greater than that of carbon tetrachloride, the liquid residue would remain noninflammable, but inflammable vapor–air mixtures could be formed from its evaporation.

Trichloroethylene and various Freon compounds may be used to advantage where liquids having noninflammable characteristics are required.

D. ELIMINATION OF IGNITION SOURCES

Combustible gases and vapors, mixed with air or pure oxygen in proportions to give inflammable mixtures, may be employed safely provided all sources of ignition are eliminated. The atmosphere in the gasoline tanks of the millions of automobiles and trucks in use on our streets and highways contains either inflammable mixtures or mixtures that become inflammable when air is added, yet the number of accidents caused by these conditions is extremely small. This is largely due to the fact that the tanks are kept closed and no sources of ignition are present in the tank or around the filler cap.

The safety engineer is primarily interested in the sources of ignition that may cause explosions. These sources may be classified as given below:

- Ignition sources
  - Flames
    - Open lights
    - Matches and cigarette lighters
    - Fires in boilers and water heaters
    - Burning material; incinerators
  - Sparks
    - Static electricity
    - Electrical shorts and arcs
    - Lightning
    - Sparks from tools
  - Heated materials
    - Glowing metals; hot cinders
    - Overheated bearings
    - Electric light filaments
    - Spontaneous combustion

Most of the sources of ignition given above can be controlled by establishing proper safety regulations and installing flameproof and vaporproof electrical equipment; others, by designing the plants so that boilers, water heaters, incinerators, and other equipments where there are open flames and incandescent materials are installed in other buildings at a safe distance from the place where the processes involving explosion hazards are carried out.

Static electricity has caused many serious fires and explosions and is one of the most difficult ignition hazards to control. There are few operations in which it may not be present. It is more serious in dry atmospheres, where the relative humidity is below 50 per cent. Static electricity may be generated by friction, that is, by slipping belts, pulleys, and revolving machinery, and by passage of solids, liquids, or gases at high velocity through small openings. It also may be generated by impact, pressure, cleavage, and induction. It may be partly or totally eliminated by the proper grounding of all machinery, pipes, and other equipment where charges may accumulate. Whenever practical there is added safety in also maintaining the room humidity above 50 per cent.

E. SEGREGATION OF HAZARDOUS OPERATIONS

Operations which, through necessity rather than choice, require the use of large volumes of inflammable gases or vapors should be segregated from other operations. This requires the installation of hazardous processes in buildings at a safe distance and, if heavy combustible vapors are involved, the elevation should be below that of other buildings, so that in case of a fire or explosion the liquids and vapors that may be released will not flow toward other adjacent buildings. Tables of safe distance for various operations involving the use of combustible liquids and vapors have not been developed, as has been done in the manufacture and storage of explosives. Therefore, it becomes the duty of the safety engineer to use his own judgment as to what distance is safe for a given operation.

F. PROVISION OF ADEQUATE VENTILATION

The necessity for adequate ventilation where inflammable gases and vapors are handled and used cannot be too strongly emphasized. This need for adequate ventilation applies not only to the spaces around the equipment in which the vapors are present but also to all conduits, trenches, and tunnels where pipes for conveying inflammable gases and vapors, and pipe lines for conveying inflammable liquids are installed. Such lines should be carried in the open air from one building to another, and in buildings they should be suspended above the floor level where they can be inspected readily for leaks.

The buildings should be of light material which will offer not too great a resistance to applied pressure if an explosion occurs. The roofs should be provided with ventilators, and windows should be installed with sashes of the tilting type that open when pressure is exerted from the inside. A reduction of pressure on the walls of the buildings following an explosion can be obtained by outside glazing and by scoring the glass panes before they are installed.[102]

It is impossible to have too much ventilation around exceedingly hazardous operations. Whenever possible the operations should be carried out entirely in the open air, as is done in certain processes in the petroleum industry, with no closed structures, except those to house instruments and other equipment that must be protected from the weather.

G. RELEASE DIAPHRAGMS AND VENTS

Adequate release diaphragms should be provided on all equipment in which explosive mixtures may be present. The ideal release diaphragm is that having zero mass and infinite area. Although this cannot be realized in practice, the construction and size of release openings should approach the above ideal as closely as possible, yet be strong enough to sustain the operating pressure within the equipment without danger of rupture or leakage, except in case of an explosion within the equipment.

To protect properly a given installation containing explosive mixtures the following major factors must be known or determined experimentally: (*1*) the type and concentration of the combustible vapor or gas that may be present in the equipment; (*2*) the maximum pressure the equipment will safely stand; (*3*) the maximum pressure developed by the mixtures on explosion; (*4*) the area of release openings necessary to keep the pressures below the safe maximum pressure; (*5*) the kind, area, and thickness of the diaphragm material that will rupture at the desired pressure; (*6*) the proper location of the diaphragms to release the pressure developed before excessive pressures are reached. For specific information on this subject the reader is referred to published reports.[103–106] Release diaphragms are now available that

[102] H. R. Brown and R. L. Hanson, *Chem. Met. Eng.*, **40**, 1030 (1929).

[103] M. E. Bonyun, *Trans. Am. Inst. Chem. Engrs.*, Preprint (May, 1935).

[104] C. E. Huff, *Chem. Met. Eng.*, **44**, 715 (1937).

[105] G. W. Jones, E. S. Harris, and B. B. Beattie, *U.S. Bur. Mines Tech. Paper* No. **553** (1933).

[106] G. F. Lake and N. P. Inglis, *Inst. Mech. Engrs. (London)*, **142**, 365 (1940).

will rupture at definite pressures ranging from less than 1 p.s.i. to 1000 p.s.i. Various types of materials are used, and they may be obtained with protective coatings where corrosive atmospheres are encountered.

One example of explosive mixtures of acetone and air will be dicussed to show how the proper diaphragms may be determined. Figure 4 gives the pressures developed when the area of release opening is varied from no opening to 45 sq. in. per cubic foot of space in the equipment. These values were obtained experimentally in an 8-liter closed bomb with mixtures containing 5.50 per cent of acetone vapor, a concentration that gives the highest pressure on explosion.

Let it be assumed that the equipment should not be subjected to a pressure greater than 10 p.s.i.; then from the results given in Figure 4 the area of release openings should be at least 5 sq. in. per cubic foot of space.

Next is the determination of the proper size and thickness of the diaphragm material that will provide release of the gases from the equipment at a pressure of 10 p.s.i. or less. In general lead, tin, aluminum, copper, gold, and special alloys have been found to be most suitable for release materials at low pressures. An example is shown of tests made on aluminum foil 0.001 in. in thickness in an 8-liter bomb using acetone–air mixtures. The rupturing pressures for openings of different sizes and for different concentrations of acetone in air on explosion are given in Figure 5. The rupturing pressures increase as the area of the opening is reduced. In our example, where the pressure must not exceed 10 p.s.i., the curves show that the diaphragms must be at least 3 in. in diameter for this particular aluminum foil; and, as previously determined, the number of release openings should give 5 sq. in. of diaphragm release opening per cubic foot of space in the equipment.

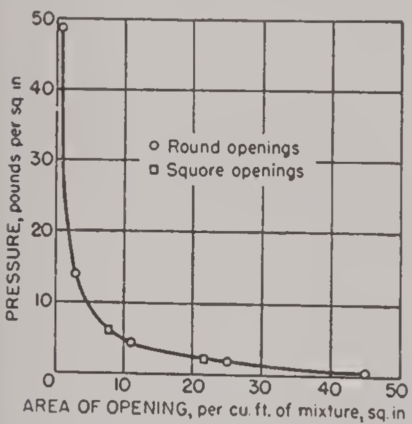

FIG. 4. Curve of relation of pressures produced to area of opening, 5.50 per cent acetone–air mixtures (8.05 liter bomb).

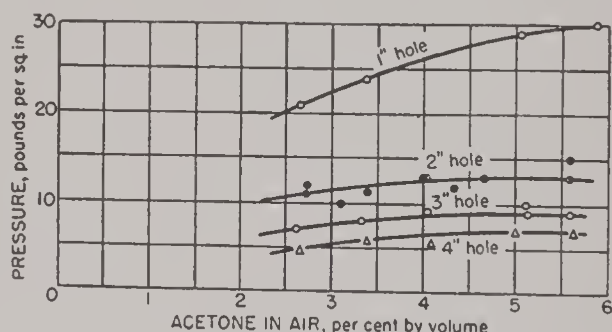

FIG. 5. Aluminum diaphragm tests (0.001 inch thickness).

The pressure required to rupture a given diaphragm material has been found by experiment[105] to be directly proportional to the ratio of the perimeter to the area. This relation can be expressed by the equation $P = KS/A$, in which P is the pressure, in pounds per square inch, required to rupture the diaphragm, A the area

in square inches, S the perimeter in inches, and K a constant characteristic of the particular diaphragm material being used.

In practice, K is determined for any given diaphragm material by testing the material in an opening of any given size and determining the pressure required to rupture the diaphragm. The determined value of K can then be used to calculate the rupturing pressure of openings of any size.

The location and spacing of the release diaphragms are very important. Experiments made in round ducts 12 in. in diameter and 15 ft. in length with acetone–air mixtures showed that the release diaphragms should be spaced not more than 10 ft. apart, and every dead end and sharp bend required a release diaphragm to prevent building up excessive pressures at these points.[105]

H. COMBUSTIBLE GAS INDICATORS FOR INFLAMMABLE ATMOSPHERES

Combustible gas indicators or recorders should be installed in all equipment where hazardous concentrations of combustibles may be present. The sampling locations should be chosen so that test mixtures may be taken from different locations. Equipment is available for taking samples periodically from 20 or more locations and recording the concentrations on one chart.

This chapter does not purpose to discuss the merits of indicators and recorders. The performance and success of any of these devices can be ascertained only by actual trial under plant operating conditions. They should be calibrated by chemical methods against the particular combustibles used in the process. The temperature of the indicator should be approximately the same as that of the space from which the samples are taken if heavy combustible vapors are being tested. If the space from which the samples are taken is at an elevated temperature, the higher vapor pressure of the combustible at this elevated temperature will liberate quantities of the vapor into the space, but when samples are withdrawn to a location at a lower temperature, part of the vapor may condense and give misleading results.

Pure gum and similar types of tubing are not satisfactory for sampling heavy hydrocarbon vapors. A 10-ft. length of rubber sampling tubing may absorb the greater part of the hydrocarbon vapor present in an atmosphere during its passage through the tubing to the indicator. Copper tubing should be used in these instances.

CHAPTER THIRTEEN – SECTION TWO

Explosion and Fire Hazards of Combustible Dusts

IRVING HARTMANN

I. The Explosion Hazard

A dust explosion may be defined as the rapid combustion of a cloud or suspension of dust in air, during which heat is generated at a much higher rate than it is dissipated to the surroundings. This phenomenon, which is similar to that of a gas explosion, is characterized by the sudden development of pressure, which frequently causes the destruction of both the plant and the equipment containing the dust. Generally speaking, any combustible solid material in finely divided form may produce a dust explosion if thrown into suspension in air and ignited. The conditions necessary for the explosion are a sufficiently dense dust cloud and an ignition source intense enough to raise the temperature of part of the dust mixture to the ignition point. It should be pointed out that coarse dust up to about 20-mesh or 710-micron size, as well as fine dust, may be involved in an explosion; it should be noted also that the dust concentrations necessary for explosions are much higher than those generally considered from a toxicological standpoint.

Tens of thousands of industrial plants in the United States are subject to the hazard of dust explosions. According to published statistics,[1] up to September 1942 780 dust explosions had occurred; 519 persons had been killed, 1206 had been injured, and the estimated property damage was nearly 56 million dollars. The explosions took place in a wide variety of establishments including grain elevators, woodworking plants, feed and cereal mills, flour mills, sugar refineries, fertilizer plants, malt houses, cotton mills, and plants producing starch and corn products. Others occurred in plants where cork dust, pulverized coal, metal dust, sulfur dust, bark dust, coffee and spice dusts, paper dust, phonograph-record dust, pitch and resin dust, rubber dust, or other combustible dusts were present.

As a result of the increased use of metal powders in powder metallurgy and in

[1] *National Fire Codes for the Prevention of Dust Explosions,* Natl. Fire Protec. Assoc., Boston, 1946.

military pyrotechnics, there have been numerous metal-dust explosions in recent years. Similarly, the number of explosions has increased in the rapidly expanding plastics industry, in which many combustible synthetic resins, molding compositions, and fillers are used in powder form. Another potential field of hazard is in the manufacture of dehydrated food products.

The following have been established as some of the definite causes of industrial dust explosions: electricity, such as sparks from motors, fuses, switches, short circuits, static electrical discharges, and breaking of incandescent lights; frictional sparks from foreign material going through grinding mills and into fans, from sledge hammers, from workmen's shoes, and from grinding wheels and buffers; hot particles, such as glowing material fed to mills or dust collectors and sparks from boilers and from locomotives; heated surfaces, such as overheated bearings and other moving parts of machines, dust settled on hot light bulbs, dust on steam coils and on hot pipes in driers, choke-ups and friction in grain elevators; open flames and lights, such as lanterns, candles, gas lights, torches, matches and smoking, and miscellaneous small-scale fires, including spontaneous ignition of waste and other materials, breaks in oil and fuel lines, and boiler backfires; small explosions of flammable vapors and of dust blown into furnace and incinerator flues; and disturbance of burning dust by use of water hose.

FACTORS AFFECTING EXPLOSIBILITY OF DUSTS

The probability of ignition of a dust cloud depends to a large degree on the temperature and the minimum energy required for its ignition. Dusts that have high ignition temperatures and require considerable energy for ignition are less likely to ignite and to produce explosions from accidental causes than are more readily inflammable dusts. However, there is little if any relation between the ignition temperature and the minimum required energy. The violence of an explosion, as manifested by the maximum pressure developed and the speed of the explosion, depends on several factors, some of which also affect the ignition temperature and the minimum energy. These include the composition of the dust, its fineness and physical structure, the concentration of the dust cloud, the composition of the gaseous atmosphere containing the dust, the nature of the ignition source, and the type of container or structure in which the explosion occurs. A brief discussion of these factors follows.

1. Composition of Dust

The ease of oxidation, the oxygen requirement for complete combustion, and the heat of combustion are specific properties of a substance which affect its explosibility. The ease of oxidation influences the ignition temperature as well as the rate of burning. The oxygen requirement determines the dust concentration at which all the dust in a given volume of air will burn. The heat of combustion has a direct relation to the maximum pressure developed during an explosion, in that the pressure is due partly to the heating of the air and of other gases by the heat of combustion of

the dust and partly to the formation of gaseous products of combustion. The amount of gas, nitrogen, remaining after combustion of aluminum and other metal powders in air is less than the initial amount of air in the combustion space; therefore in this case the pressure developed is due entirely to the expansion of the nitrogen by the available heat. Similarly, when carbon burns in air the volume of carbon dioxide and nitrogen after combustion is the same as the volume of air beforehand. On the other hand, when sugar or starch dust burns in air the volume of gaseous combustion products, carbon dioxide, nitrogen, and water vapor, will be greater than the volume of air beforehand. Since the dust must be heated to its ignition temperature before it ignites and the combustion products, solid as well as gaseous, are heated during the explosion, it is evident that the specific heats of these substances also influence the pressure that may be developed.

The purity of a dust has an important effect on its inflammability. High percentages of incombustibles, whether inherent in the form of mineral matter and moisture or other volatile incombustibles, or added inert, reduce the hazard of ignition and explosion through their cooling and possibly inhibiting action.

Many dusts contain volatile combustible matter that is given off below the ignition temperature of the dusts. This in general promotes ignition of the dusts and makes them more explosive. The effect is illustrated for coal dusts in a paper by Greenwald[2] and for pulverized fuel pitch in a paper by Hartmann, Howarth, and Greenwald.[3]

Some dusts, including metal powders such as aluminum, iron, lead, magnesium, and others, under certain conditions combine with nitrogen in the air to form nitrides. When this happens during a dust explosion the heat of formation of the nitride as well as that of the oxide may come into play to determine the maximum pressure developed. Furthermore, in such circumstances a much higher concentration of dust could be burned in a given volume of air than when only the oxide is formed.

2. *Fineness and Physical Structure of Dust*

For a number of reasons, the fineness of dust particles has a vital effect on explosibility. Fine dust can be thrown into suspension more easily, it disperses more uniformly, and remains in suspension longer than does coarse dust, so that the chances for explosions are greater from fine dust. During disintegration of a solid into powder and during subsequent exposure of the powder an air film is formed by adsorption on the surface of the particles, which appears to promote ignition. The amount of gas adsorbed on fine particles is proportionately greater than on coarse ones. During the movement of dust through air, as a result of friction with the air and impact and friction of the particles against each other and against the walls of the containing vessel, an electrical charge is developed on the particles, a condition

[2] H. P. Greenwald, *U.S. Bur. Mines Repts. Investigations* No. 3489 (1940).

[3] I. Hartmann, H. C. Howarth, and H. P. Greenwald, *U.S. Bur. Mines Tech Paper* No 617 (1940).

that promotes ignition of the dust cloud. The electrical capacity as well as the charge in a dust cloud of given concentration increases with the fineness of the particles. The combined effect of these factors and of the small mass of fine dust particles results in lower ignition temperature, lower minimum energy requirement for ignition, and lower minimum explosive concentration in clouds of fine dust than in those composed of coarse dust. Furthermore, since in a fine dust cloud there is a greater number of particles with a greater total surface area and the particles are spaced together more closely than the particles in a cloud of equal weight concentration of coarse dust, the rate of flame propagation is greater and the heat losses are smaller in the fine dust cloud, and therefore higher maximum pressures are generally developed during explosions. These effects are illustrated for dusts of synthetic resins and molding compositions in several curves in a paper by Hartmann and Nagy.[4]

An extreme example of the effect of fineness on inflammability is manifested in the pyrophoric behavior of certain magnesium, lead, iron, and other metal powders. When of very fine size, these powders oxidize so rapidly upon exposure to air that they ignite spontaneously.

Dusts of a given material produced by different manufacturing processes may have different shapes and surface characteristics that affect their inflammability. This may be due to a difference in surface area, density, the amount of adsorbed gases, or the formation of protective surface layers. It is known, for example, that aluminum and magnesium powders produced by stamping, which yields flat, thin particles, have higher inflammability than approximately spherical particles of the same mesh size produced by atomization or by milling.

3. Concentration of Dust Cloud

In a dust cloud, just as in a gas-air mixture, ignition of one part of the cloud will be propagated throughout the entire mixture and develop into an explosion only when the concentration of dust in the air is between certain lower and upper limits. The minimum explosive concentration or lower limit of explosibility is that concentration at which there is just barely enough dust in the air to propagate flame throughout the cloud after ignition at a localized point.

The upper explosive limit is theoretically that dust concentration at which the heat generated through complete combustion of a portion of the dust in all the oxygen available is insufficient to raise the entire dust cloud to the ignition temperature.

Between these two limits there is an "optimum" concentration at which there is just enough dust in the cloud for complete combustion in the available oxygen. The pressure developed and the speed of the explosion at this dust concentration under most favorable conditions will be greater than at lower or higher concentrations. The effect of concentration on the maximum pressures developed and the rates of pressure rise in explosions of dust clouds of stamped aluminum powder can be seen in Figure 6.

[4] I. Hartmann and J. Nagy, *U.S. Bur. Mines Repts. Investigations* No. 3751 (1944).

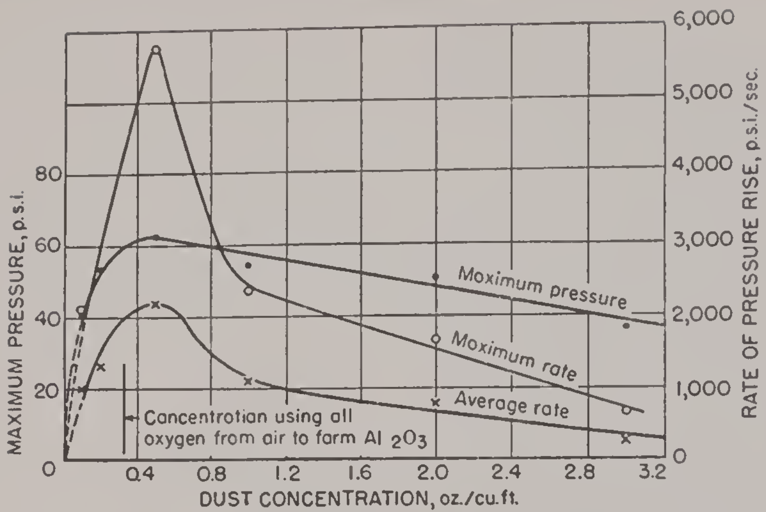

FIG. 6. Maximum pressure and rates of pressure rise developed during explosions of aluminum powder at various concentrations.

4. *Composition of Atmosphere*

The percentage of oxygen in the gaseous atmosphere containing a dust cloud affects its inflammability. Decrease in oxygen content reduces the ease of ignition and, in general, also the violence of explosion produced by a dust cloud. This effect is illustrated in Figure 7 for four powders used in the plastics industry. For most dusts there exists a critical oxygen limit, below which they will not ignite; for the samples in Figure 7 this limit is 14.5 per cent oxygen. Exceptions to this have been found in a few metal powders, including zirconium, magnesium, titanium, and some magnesium-aluminum alloy powders, that ignited by spark and propagated flame when dispersed in carbon dioxide. For reducing the inflammability of most carbonaceous dusts, reduction of the oxygen content by dilution of air with carbon dioxide proved to be somewhat more effective than dilution to the same degree with nitrogen. The reason appears to be the higher specific heat per unit volume and therefore the greater cooling action of carbon dioxide than of nitrogen. For a few metal powders, however, dilution of the air with nitrogen was more effective than

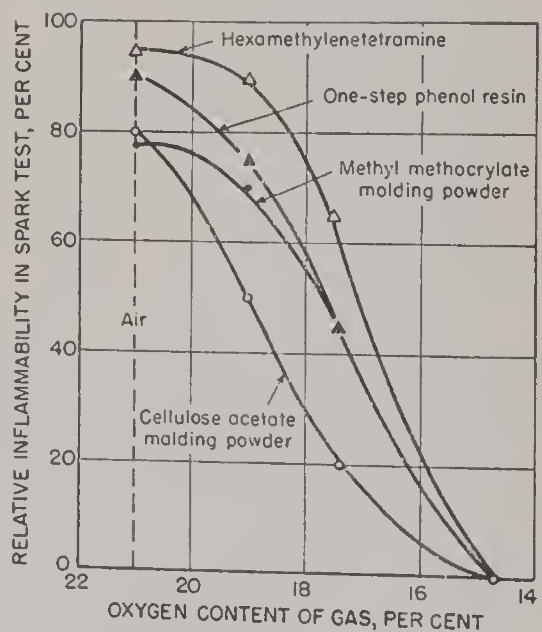

FIG. 7. Inflammability of plastic powders in mixtures of air and carbon dioxide.

dilution with carbon dioxide, probably because the metal could decompose carbon dioxide more easily than it could combine with nitrogen.

Available evidence indicates that ordinary variations in atmospheric humidity have little direct effect on the inflammability of dust clouds, except to the extent that the dust absorbs moisture and requires more heat for ignition. However, high atmospheric humidity does make the air a better conductor of electricity, thereby promoting leakage of static electrical charge from the dust cloud and reducing the hazard of ignitions from static sparks. This may be quite important, especially with nonconducting dusts, on which considerable static charge might be developed in dry air.

5. Type of Ignition Source

Experiments have shown that when dust clouds are in contact with an ignition source for some time, so that the dust and air are preheated, they can be ignited at lower temperatures than is possible by instantaneous contact with the heat source. It is also known that ignition can be effected at a lower temperature by large ignition sources, which come in contact with a greater portion of the dust cloud, than by localized ignition sources. Most carbonaceous and many other dusts are more difficult to ignite by electric sparks or arcs than by open flames and hot surfaces. There is some evidence to indicate that the minimum explosive concentration of a dust cloud also is affected somewhat by the nature of the ignition source.[5]

6. Characteristics of Explosion Space

Although no controlled studies have been made concerning the exact effects of the size, shape, and other characteristics of containers or rooms in which dust explosions occur, it is known that they influence the distribution of the dust cloud, the propagation of flame through the cloud, and the rate of pressure rise during an explosion. There is some evidence to show that explosions of a dust cloud of given concentration will produce higher maximum unit pressures in a large chamber than in a smaller space. It is also known that more violent explosions are developed in a turbulent dust cloud, as in a grinding mill, than in a still cloud of the same concentration.

II. Laboratory Data on Dust Explosibility

Studies of the explosibility of dusts have been made by numerous investigators here and abroad, and data have been obtained on ignition temperatures, minimum explosive concentrations, maximum pressures, and other related factors. Unfortunately the results published by different authors vary widely, owing in part to the great difficulty of producing and maintaining uniform dust clouds in test equipment, difference in experimental procedure, and variation in supposedly similar dust samples, especially in regard to purity and fineness. For these reasons it does not seem wise to report here more than a few detailed results. For further information the reader will be referred to publications that he can consult.

In this country most of the experimental work on dust explosions has been

[5] L. J. Trostel and H. W. Frevert, *Chem. Met. Eng.*, **30**, 141 (1924).

conducted by the Bureau of Mines of the United States Department of the Interior at its Pittsburgh, Penna. laboratory; by the Bureau of Agricultural Chemistry and Engineering of the United States Department of Agriculture, Washington, D. C.; by the engineering department of the Factory Insurance Association, Hartford, Conn.; by the laboratory of the Associated Factory Mutual Insurance Cos., Boston, Mass.; and by the Underwriters' Laboratories, Inc., Chicago, Ill. A good account of early experimental work, together with descriptions of many industrial dust explosions, is given by Price and Brown.[6] A brief discussion of the problem, with extracts of experimental data from various sources, is given by Gibbs.[7] Many studies are described in reports and pamphlets issued by the organizations named above. A list of references to work of foreign investigators is included in the bibliography of a dissertation by Brown.[8]

A. DATA ON IGNITION TEMPERATURES

The ignition temperature of solids can be defined in many ways, and various tests have been devised to determine the temperature according to the definition used. A commonly used definition that may be accepted for the present purpose is "that temperature at which the substance takes fire spontaneously in air."

Trostel and Frevert[5] determined the ignition temperatures of dust clouds of several substances by igniting them with a small, heated platinum coil. For the dusts tested in minus 200-mesh (74-μ) size the results in Table 8 were obtained.

TABLE 8

Dust	Ignition temperature, °C.	Dust	Ignition temperature, °C.
Sulfur	280	Sugar	650
Corn-elevator	625	Wheat-elevator	700
Cornstarch	640	Aluminum	925

Edwards and Harrison[9] determined the ignition temperatures of quiescent layers of various dusts during prolonged heating in an electric furnace through which air was passed at a definite rate. They reported the values given in Table 9.

In a study on the explosibility of metal powders, at the Bureau of Mines laboratory,[10] the ignition temperatures of dust clouds of the powders were determined by projecting them through a heated laboratory furnace, and the ignition temperatures of quiescent dust layers were measured by heating them in the furnace for several minutes. In nearly all cases, 90 per cent or more of each powder was finer than 200-mesh. Selected results are given in Table 10.

[6] D. J. Price and H. H. Brown, *Dust Explosions, Theory and Nature of, Phenomena, Causes and Methods of Prevention.* Natl. Fire Protect. Assoc., Boston, 1922.

[7] W. E. Gibbs, *The Dust Hazard in Industry.* Ernest Benn, Ltd., London, 1925.

[8] C. R. Brown, *The Determination of the Ignition Temperatures of Solid Materials* Catholic Univ. of America, Washington, 1934.

[9] P. W. Edwards and R. W. Harrison, *Ind. Eng. Chem., Anal. Ed.*, **2**, 344 (1930).

[10] I. Hartmann, J. Nagy and H. R. Brown, *U.S. Bur. Mines Repts. Investigations* No 3722 (1943).

Under test conditions similar to the above, dust clouds of Pittsburgh bed coal ignited at 610°, peat moss at 475°, and cornstarch at 380° C.

In a Bureau of Mines study[4] of the explosibility of powders used in the plastics industry the selected, dust-cloud ignition temperatures given in Table 11 were determined.

TABLE 9

Dust	Ignition temperature, ° C.	Dust	Ignition temperature, ° C.
Cellulose	354	Paper	337
Cocoa	237	Pyrethrum flowers	252
Corn-elevator	267	Tobacco	253
Cornstarch	324	Wheat-elevator	265
Ground cloves	253	Wheat smut	255
Ground oat hulls	272	Wood flour	277
Hard-wheat flour	327	Wood-pulp	272
Leather-fertilizer	324		

TABLE 10

Dust	Ignition temperature, ° C.		Dust	Ignition temperature, ° C.	
	Dust cloud	Dust layer		Dust cloud	Dust layer
Aluminum, atomized	700	—	Lead, atomized	710	270
Aluminum, stamped	645	585	Lead, stamped	580	300
Antimony	415	330	Magnesium, stamped	520	475
Cadmium	570	250	Magnesium, milled	540	490
Chromium	900	—	Manganese	450	450
Copper	700	—	Silicon	775	950
Dowmetal	430	480	Tin	630	430
Iron, carbonyl	320	310	Titanium	480	460
Iron, hydrogen reduced	315	290	Zinc	600	460
Iron, carbon reduced	425	390	Zirconium	20[a]	210
Iron, milled	780	460			

[a]Ignition of zirconium dust cloud at room temperature may have been caused by static-spark discharge within cloud.

TABLE 11

Powder: Resins	Ignition temperature, ° C.	Powder: Molding compositions	Ignition temperature, ° C.
Shellac, rosin, gum	390	Cellulose compounds	320
Vinylbutyral	390	Synthetic rubber	320
Cellulose acetate	410	Methyl methacrylate	440
Lignin	450	Urea	450
Urea	470	Phenolic	490
Polystyrene	490	Polystyrene	560
Phenolic	500	Vinyl chloride – vinyl acetate	690
Coumarone-indene	520		
Chlorinated paraffin	840		
Resin ingredients	**° C.**	**Fillers for molding compositions**	**° C.**
Hexamethylenetetramine	410	Ground alpha pulp	480
Pentaerythritol	450	Ground cotton flock	470
Rennet casein	520	Ground wood flour	430
Phthalic anhydride	650		

B. MINIMUM EXPLOSIVE CONCENTRATION

There is probably greater disagreement in values reported by different investigators on minimum explosive concentrations of dust clouds than on any other explosibility factor, because the distribution of the dust cloud, which varied according to the experimental procedure, is very important in the determination, and because different interpretations were placed on what constitutes a feeble explosion, such as is obtained at this low concentration. For aluminum powder the published values[11] range from 7 to 432 mg. per liter, and for sugar dust they range from 10.3 to 370 mg. per liter.[5] A dust concentration of 1 mg. per liter is approximately equal to 1 oz. per 1000 cu. ft.

Table 12 lists selected values for minimum explosive concentrations of metal powders and of plastic powders determined in the Bureau of Mines investigations previously mentioned.

TABLE 12

Powder — Metal	Minimum concn., mg./liter	Powder — Metal	Minimum concn., mg./liter
Aluminum, atomized	40	Magnesium, milled	20
Aluminum, stamped	35	Manganese	210
Antimony	420	Silicon	160
Dowmetal	20	Tin	190
Iron, carbonyl	105	Titanium	45
Iron, hydrogen reduced	120	Zinc	480
Iron, carbon reduced	250	Zirconium	190[a]
Magnesium, stamped	20		
Resins	**Concn.**	**Molding compositions**	**Concn.**
Cellulose acetate	35	Cellulose compounds	25
Coumarone-indene	15	Methyl methacrylate	20
Lignin	40	Phenolic	30
Phenolic	25	Polystyrene	15
Polystyrene	20	Synthetic rubber	30
Shellac, rosin, gum	15	Urea	75
Urea	70		
Vinylbutyral	20		
Resin ingredients	**Concn.**	**Fillers for molding compositions**	**Concn.**
Hexamethylenetetramine	15	Ground alpha pulp	60
Pentaerythritol	30	Ground cotton flock	50
Phthalic anhydride	15	Ground wood flour	40
Rennet casein	45		

[a] A recent test on a different sample of zirconium powder gave a value of 40 mg. per liter.

Approximate values for various miscellaneous dusts of minus 200-mesh size are given in Table 13.

Very little experimental work has been done on determinations of optimum concentrations and of maximum explosive concentrations of dust clouds. Values of optimum concentrations for many metal powders have been computed, however.[10]

[11] R. B. Mason and C. S. Taylor, *Ind. Eng. Chem.*, **29**, 626 (1937).

TABLE 13

Dust	Minimum concn., mg./liter	Dust	Minimum concn., mg./liter
Almond flour	150	Paddy rice flour	180
Clover seed	60	Pea flour	50
Cork	50	Peat moss	30
Cornstarch	40	Pittsburgh seam coal	55
Cracked wheat	60	Salicylic acid	20
Garlic flour	100	Soy flour (full fat)	65
Hard rubber (from high-grade crude)	25	Sugar	50
Onion flour	130	Sulfur	30
		Wheat flour	60

C. MINIMUM ENERGY REQUIRED FOR IGNITION

The minimum energy needed for ignition of dust clouds of many metal powders and of plastic powders was measured at the Bureau of Mines laboratory. In this work a condenser was charged to some definite potential, and formation of the dust cloud in the explosion vessel was synchronized with discharge of the condenser through the primary winding of a step-up transformer. The potential induced in the secondary circuit of the transformer produced a spark between electrodes in the dust cloud. Condensers of different capacities were used to determine the weakest spark needed to ignite the dust clouds.

In the metal powder group it was found that less than 0.04 joule was needed to ignite zirconium and magnesium powders (1 joule = 0.00095 B.t.u.); less than 0.1 joule was needed for aluminum, Dowmetal, carbonyl and hydrogen-reduced iron; less than 0.2 joule for tin and titanium; from 0.3 to 2.0 joules for antimony, carbon-reduced iron, manganese, silicon, and zinc; and 4 joules for cadmium.

In the plastics group dust clouds of the following resins and molding compounds ignited by static sparks of 0.01 joule energy: shellac, rosin, gum, phenolic, coumarone-indene, vinylbutyral, cellulose acetate; 0.02 joule or less was needed for lignin and methyl methacrylate; 0.03 joule for synthetic rubber; 0.04 joule for polystyrene molding powder; and 0.08 joule for urea powders.

The study is being continued to determine how variations in the voltage, length of spark, and other factors affect minimum energy requirements. Preliminary tests indicate that under certain conditions dust clouds of the powders listed above can be ignited by even weaker sparks than shown above.

D. MAXIMUM PRESSURE AND RATES OF PRESSURE RISE IN DUST EXPLOSIONS

The maximum pressure developed and rates of pressure rise indicate the seriousness of a dust-explosion hazard and provide information that can be used in determining the type and amount of venting that must be provided in a building or machine to release explosion pressures before structural damage occurs. Data of this type for 133 agricultural and other dusts were obtained in the laboratory of the United States Department of Agriculture and are published in a paper by Edwards and Leinbach;[12] for metal powders and plastic powders information was obtained at

[12] P. W. Edwards and R. L. Leinbach, *U.S. Dept. Agr. Tech. Bull.* No. 490 (1935).

the Bureau of Mines laboratory.[4, 10] Following are selected values of maximum pressures obtained in these studies; for rates of pressure rise and for other details the reader is referred to the original papers. The pressures given below were determined at dust-cloud concentrations of 500 mg. per liter and are not necessarily the highest pressures that might be developed in explosions of the dusts, but sufficient data are not available for many dusts at different concentrations. The following selected data in Table 14 are from the paper of Edwards and Leinbach. From the Bureau of Mines reports the data in Table 15 have been selected.

TABLE 14

Dust	Explosion pressure, p.s.i.	Dust	Explosion pressure, p.s.i.
Cork and other barks	40	Carbon, coal, etc.	48
Fertilizers	51	Cocoa	23
Grain	46	Drugs	43
Milk powders	42	Flours	42
Starches	47	Meals	41
Sugars	45	Resins, soaps, waxes	42
Sulfur	32	Spices	43
Woods	44		

TABLE 15

Powder	Explosion pressure, p.s.i.	Powder	Explosion pressure, p.s.i.
Metal		Metal	
Aluminum, atomized	58	Magnesium, milled	65
Aluminum, stamped	62	Manganese[a]	25
Antimony[a]	6	Silicon	62
Dowmetal	56	Tin[a]	26
Iron, carbonyl[a]	29	Titanium[a]	44
Iron, hydrogen reduced	26	Zinc[a]	13
Iron, carbon reduced[a]	25	Zirconium[a]	31
Magnesium, stamped	72		
Resins	Pressure	Molding compositions	Pressure
Cellulose-acetate	68	Cellulose compounds	62
Coumarone-indene	63	Methyl methacrylate	57
Lignin	69	Phenolic	63
Phenolic	61	Polystyrene	50
Polystyrene	44	Synthetic rubber	59
Shellac, rosin, gum	58	Urea	63
Urea	65		
Vinylbutyral	60		
Resin ingredients	Pressure	Fillers for molding compositions	Pressure
Hexamethylenetetramine	64	Ground alpha pulp	60
Pentaerythritol	65	Ground cotton flock	67
Phthalic anhydride	49	Ground wood flour	62
Rennet casein	49		

[a]For these powders higher pressures were measured at a dust-cloud concentration of 1.0 g. per liter; the values, in pounds per square inch, were as follows: antimony, 20; iron, carbonyl, 31; iron, carbon-reduced, 36; manganese, 31; tin, 34; titanium, 52; zinc, 36; zirconium, 42.

E. RELATIVE INFLAMMABILITY OF DUSTS

Another system of classifying the explosion hazards of dusts, which was developed on the basis of work with coal dusts in experimental mine work and in the laboratory, is to group them according to their "relative inflammability." This is defined as the percentage by weight of an inert dust (generally calcined fuller's earth in the laboratory and limestone dust in large-scale work) required in a mixture with the inflammable dust to prevent ignition and flame propagation when the mixture is dispersed into a cloud in the presence of an igniting source. Standard igniting sources used in these tests at the Bureau of Mines laboratory are an electrically heated, vertical, cylindrical furnace at a temperature of 700° C. and a high-voltage, low-wattage (20 to 24 watts) electric spark. Table 16 lists the relative inflammabilities of a number of metal powders and of powders used in the plastics industry. A relative inflammability of 90+ indicates that a mixture containing 90 per cent inert dust ignited and propagated flame under the test conditions.

TABLE 16

Powder	Relative inflammability, percentage		Powder	Relative inflammability, percentage	
	In furnace test	In spark test		In furnace test	In spark test
Metal			*Resins*		
Aluminum, atomized	10	78	Cellulose acetate	90+	83
Aluminum, stamped	60	80	Coumarone-indene	90+	90+
Antimony	65	18	Lignin	90+	78
Cadmium	18	0	Phenolic	90+	90
Chromium	0	0	Polystyrene	90+	90+
Copper	3	0	Shellac	90+	90+
Dowmetal	90	90	Urea	85	60
Iron, carbonyl	85	60	Vinylbutyral	90+	80
Iron, hydrogen reduced	90+	55			
Iron, carbon reduced	90+	43	*Molding compositions*		
Magnesium, stamped	90+	90+	Cellulose compounds	90+	90
Magnesium, milled	90+	90	Methyl methacrylate	90+	78
Manganese	40	25	Phenolic	90+	80
Silicon	0	33	Polystyrene	90+	90+
Tin	10	30	Synthetic rubber	90+	80
Titanium	55	78	Urea	90+	68
Zinc	35	45	Vinyl chloride–vinyl acetate	5	0
Zirconium	90+	90+			

III. The Fire Hazard

From what has been said on the preceding pages it is evident that the fire hazard in handling dusts of combustible materials is considerably greater than for the same materials in bulk. In general the dusts ignite at lower temperatures, they burn more rapidly, and the fires are more difficult to extinguish than for larger pieces.

The ignition temperatures of quiescent layers of many carbonaceous dusts and several metal powders have been listed in foregoing tables. These temperatures are one index of the fire hazard of the dusts. For the metal powders there was also

determined the minimum spark energy needed for ignition of dust layers.[10] It was found that powders of many pure metals can be ignited by sparks having an energy of only 0.1 joule or less. This shows that fires in dusts might be started by weak electric sparks or arcs, including static sparks, as well as by heating from hot surfaces, open flames, or other causes.

Under ordinary circumstances of storage and handling, most dusts oxidize so slowly that the heat of oxidation does not produce an appreciable rise in temperature of the dust. However, there are some dusts that are subject to rapid self-oxidation; these develop enough heat to ignite spontaneously under certain conditions.

A number of metal powders and other dusts absorb moisture readily when exposed to humid air.[10] In some dusts, as aluminum, magnesium, and zinc, this moisture promotes oxidation and heating, sometimes to the point of self-ignition. Apparently when these powders are in contact with moisture there is some ionization, and the nascent hydrogen that is formed reduces the protective oxide film on the metal particles, thereby facilitating self-ignition.

Undue vibration or other disturbance of dusts is a source of trouble, not only because it promotes formation of dust clouds, but because the particles take on electrical charges, when so disturbed, that might result in the formation of sparks and possible ignition.

PREVENTION OF DUST EXPLOSIONS AND FIRES

The problem of prevention of dust explosions is of such paramount importance in industrial plants that considerable effort has been devoted to its solution. To this end the Dust Explosion Hazards Committee of the National Fire Protection Association has formulated a series of safety codes[1] that embody detailed recommendations and regulations for a number of industries. The reader is referred to these codes as a helpful guide in the design and construction of buildings and equipment and in regard to safe operating procedures. So far codes have been completed for the following operations and situations:

1. Aluminum-bronze powder manufacture
2. Coal pneumatic cleaning plants
3. Flour and feed mills
4. Pulverized-fuel systems
5. Spice-grinding plants
6. Starch factories
7. Pulverizing systems for sugar and cocoa
8. Terminal grain elevators
9. Wood-flour manufacturing establishments
10. Woodworking plants
11. The use of inert gas for fire and explosion prevention
12. Sulfur dust
13. Suggested good practices for application of suction and venting for the control of dust in grain elevators and storage units
14. Country grain elevators
15. Magnesium powder or dust
16. Plastics industry
17. Pulverized-coal systems

Important recommendations in these codes include:

(*a*) All possible sources of ignition should be eliminated from equipment containing inflammable dust and from areas surrounding such equipment. This means the prohibition of open flames or lights and of smoking; the avoidance of the use of electric or gas cutting or welding equipment for repair work unless dust-producing machinery in that part of the plant is shut down and the vicinity is entirely dust-

free; grounding of all machinery capable of producing static sparks; provision of conduits for electric wiring and location of switches and motors outside, or use of dustproof types; strict adherence, in installation of wiring and electrical equipment, to the rules of the National Electrical Code pertaining to hazardous locations; the use of electromagnetic separators to prevent entrance of ferrous materials to dust-grinding mills; use of nonferrous blades in fans through which dust passes; and avoidance of the use of high-speed shafting and belts wherever possible.

(*b*) Buildings should be constructed to avoid the collection of dust on beams, ledges, and other surfaces, particularly overhead. Good housekeeping is a prime essential in preventing dust accumulation and dissemination. In removal of dust, vacuum cleaning is preferable, although soft push brooms may be used without serious hazard. Buildings in which inflammable dusts are produced or stored should be detached units of incombustible construction, including inside partitions; and hazardous areas within buildings should be separated by substantial fire walls.

(*c*) Equipment wherein dust clouds may be produced, as grinders, conveyors, elevators, or collectors, should be as dust-tight as possible; it should have the smallest practical interior volume; and it should be constructed strong enough to withstand explosion pressures from the dust.

(*d*) Properly designed and proportioned and properly distributed vents, in the form of hinged windows, panels, or light wall construction in rooms, and the use of adequate release diaphragms or other vents in equipment, will release explosion pressures without structural damage. The proper areas for vents depend on several factors, including the strength of the structure or equipment, the pressures and rates of pressure rise developed in explosions of the dust, etc. Recommended venting areas range from 1 sq. ft. per 15 cu. ft. of volume to 1 sq. ft. per 80 or more cu. ft., depending on the factors involved.[13, 14]

(*e*) Dust collectors preferably should be located outside buildings or in detached rooms provided with adequate explosion vents.

(*f*) Grinding and conveying equipment can frequently be protected by introducing a continuous flow of inert gas into the equipment, thereby reducing the normal oxygen content to a point at which the dust will not explode.[15] The inert gas for this purpose can be obtained by diluting air with flue gases from boilers, internal-combustion engines, or other sources; or by diluting with nitrogen or carbon dioxide from high-pressure cylinders, or with gas from inert gas generators.

The maximum allowable percentages of oxygen in inert gases used for preventing the explosion of various dusts have been determined, and some of the data are given below; the figures given are based on the addition of carbon dioxide to air. To take care of somewhat stronger sources of ignition than were used in the laboratory tests and to allow for slight variations in the inert-gas supply, it is well to keep the

[13] I. Hartmann and J. Nagy, *U.S. Bur. Mines Repts. Investigations* No. **3924** (1946).
[14] H. R. Brown and R. L. Hanson, *Quart. Natl. Fire Protect. Assoc.* (Apr. 1933).
[15] H. R. Brown, *U.S. Dept. Agr. Tech. Bull.* No. **74** (1928).

oxygen content 1 or 2 per cent lower than the figures here listed, that is, if a value of 16 per cent oxygen is given, it would be safer in practical application to limit it to 14 or 15 per cent.

Data for carbonaceous dusts and for sulfur and rubber dusts were determined by Brown and Clement,[16] Edwards and Harrison,[17] Frevert,[18] and others, and these dusts are listed in the code on inert gases of the National Fire Protection Association[1] (Table 17).

TABLE 17

Dust	Maximum permissible oxygen, per cent	Dust	Maximum permissible oxygen, per cent
Cotton in bulk to prevent smoldering and reignition	8	Pittsburgh coal dust	16
Cotton lint or dust	15	Pyrethrum flower dust	15.5
Cork dust	14.1	Sulfur	11
Ground oat hulls	13.7	Wheat, corn, or oat elevator dust	14
Hard-rubber dust	13	Wheat starch	12
Jute	8	White dextrin	12

Data for metal powders and powders used in the production of plastics were determined in a spark-ignition apparatus at the Bureau of Mines laboratory.[4, 10] Selected values for some of these dusts are given in Table 18.

TABLE 18

Powder	Maximum permissible oxygen, per cent	Powder	Maximum permissible oxygen, per cent
Metal		*Synthetic resins*	
Aluminum, atomized	3	Cellulose acetate	14.7
Antimony	16	Coumarone-indene	14.7
Iron, carbonyl	10	Lignin	17.2
Iron, hydrogen reduced	13	Phenolic	14.7
Iron, carbon reduced	14	Polystyrene	16.9
Magnesium	([a])	Shellac	14.7
Manganese	15	Urea	17.2
Silicon	15	*Molding compositions*	
Tin	16	Cellulose compounds	11.9
Titanium	([a])	Methyl methacrylate	14.7
Zinc	10	Phenolic	14.7
Zirconium	([a])	Urea	17.2

[a]These powders ignited by spark even in carbon dioxide, therefore air-carbon-dioxide mixtures cannot be used for them. They did not ignite by spark in nitrogen. However, at elevated temperatures these powders burned in nitrogen as well as in carbon dioxide.

[16] H. H. Brown and J. K. Clement, *Ind. Eng. Chem.*, **9**, 347 (1917).
[17] P. W. Edwards and R. W. Harrison, *Chem. Met. Eng.*, **35**, 479 (1928).
[18] H. W. Frevert, *Chem. Met. Eng.*, **31**, 894 (1924).

In addition to the use of inert gas, it is sometimes feasible to prevent the formation of explosive dust-air mixtures in grinding equipment by the addition of inert dusts to the inflammable dust, a similar procedure to that employed in coal mines for preventing the propagation of coal-dust explosions.

Sometimes it is also possible to make use of high atmospheric humidity in the equipment or room containing inflammable dust. High humidity will reduce the ease of dispersion of dust into the air and also make ignition somewhat more difficult. As a rule, however, this practice is not recommended, because the dust still can be thrown into suspension and ignited by a strong ignition source. The usefulness of high humidity is chiefly in preventing or reducing the accumulation of static electricity on the dust.

(*g*) With respect to fire prevention and fire extinguishing in inflammable dusts, in addition to the usual recommendations for fire prevention, the following points should be noted: (1) Attention should be directed to the hazard of possible spontaneous heating in many powdered products, particularly after grinding. (2) First-aid protective equipment should be installed that is suitable for fires in combustible dusts, such as small hose, water pails, soda–acid extinguishers, and hand-operated water pump tanks. A small hose equipped with a spray-type nozzle is particularly satisfactory for most dust fires. The fine spray wets the dust and is not as apt to produce a dust cloud as is a solid stream. (3) Large hose streams of fire-department sizes should be used only with great caution where combustible dusts are involved, because dust may be thrown into suspension by their use, with a consequent explosion. Plant employees and the fire department should be advised of this danger in advance of trouble. (4) Spray or fog nozzles may be used without danger of disturbing dust deposits, and nozzles of this type should be available with all hose used for fire protection where combustible dust is present. (5) Small fires in magnesium or aluminum powder are best extinguished by sand, talc, or other dry inert materials applied gently to smother the fire, or by the use of such materials as hard pitch, which completely seal the powder from the air.[19]

[19] H. R. Brown, I. Hartmann, and J. Nagy, *U.S. Bur. Mines Repts. Investigations* No. **3672** (1942).

CHAPTER FOURTEEN

Respirators and Respiratory Protective Devices

FRANK A. PATTY

I. Historical Résumé and Present Approval Procedure

A respirator is defined as a device covering the mouth or nose, to prevent the inhalation of noxious substances. The oldest record we have of the use of such a device is that given in the first century A. D. by Pliny the Elder, who wrote of minium refiners wearing bladders over their faces to avoid inhaling mercury-bearing dust. Gas masks, oxygen-supplying apparatus, and hose masks (diving helmets) were introduced into Europe during the nineteenth century but they did not come into general industrial use until after World War I. Oxygen-breathing apparatus was introduced into the United States about 1907. Its first general usage came in 1910 with its adoption for mine-rescue work. The canister gas mask was introduced into this country when the United States Bureau of Mines was assigned the problem of developing a military mask for the American soldiers in 1917. This work later grew into the Research Division of the Chemical Warfare Service. A good serviceable mask for war uses was developed, and at the end of the war, work was continued by the Bureau with a view toward the development of an industrial mask.

Many of the military masks of the acid-gas and organic-vapor type were thrown on the market by salvage dealers after the war, but were used by returning soldiers for protection against all gases. This error was encouraged by some of the dealers who made extravagant claims concerning the masks. As a result there were many poisonings, mainly nonfatal, around ammonia refrigerating plants and among fire fighters who were exposed to carbon monoxide. The alarm caused by these poisonings produced an extensive educational campaign through newspapers, the technical press, and personal instruction. Research gradually developed canisters for various gases, and the universal canister that protects against all common gases or combinations of gases. The next step was the development of the hose mask, which is simple and foolproof, and which offers respiratory protection in any situation that can be reached by 150 ft. of hose.

In each instance, however, personal respiratory protective apparatus that really offered dependable protection was not made available in the United States

until the United States Bureau of Mines set up approval schedules and procedures for permissibility tests. These schedules[1-5] are revised from time to time to conform with advances in research and development. It was not until 1935 that effective dust respirators became available to American industry, when the first respirator passed the official schedule of tests. Scores of inferior, and in many instances useless, devices were discarded after these tests demonstrated their unsatisfactory performance.

These tests now cover oxygen-breathing apparatus, canister gas masks, hose masks, abrasive blasting and other air-line respirators, filter-type dust respirators, and chemical cartridge respirators. The tests specify the minimum permissible performance and the maximum permissible resistance to inhalation and exhalation. Certificates of approval issued by the Bureau for the accepted devices are the basis for all lists of approved industrial respiratory protective equipment, published by any agency in the United States. No data are published enabling the public to choose the respirator giving the best performance, but lists of all devices meeting the minimum requirements are published. However, these requirements are raised occasionally to keep pace with the more progressive manufacturers, and holders of early approvals are encouraged to improve the performance of their devices to meet these higher standards in order to retain the approval label. Nominal fees charged for approval testing vary with the time required for men to perform the scheduled tests. All approved devices are stamped with an approval label or number, such as BM-1400, in which the first two digits of the number refer to the schedule of tests under which the device was approved, and the last two are specific for the particular device.

II. Types and Uses of Respiratory Protective Devices

Respiratory protective devices are used to supplement other methods of control and are more frequently used as an emergency measure. Respiratory protection against all classes and combinations of air contaminants is available under two general classifications: (*1*) air-purifying respirators, which purify the air by removal of the contaminant, and (*2*) atmosphere-supplying respirators, which supply respirable, uncontaminated air or oxygen to the wearer.

A. AIR-PURIFYING RESPIRATORS

Air-purifying respirators provide protection only by removing specific contaminants from the atmosphere. Obviously, sufficient oxygen must already be present in the atmosphere to support life.

1. Gas Masks (Canister Type)

A canister gas mask usually consists of a full facepiece connected by a flexible breathing tube to a canister containing materials for purifying the air, and equipped

[1] [self-contained breathing apparatus], *U.S. Bur. Mines, Schedule* **13C** (1946).
[2] [Gas Masks], *U.S. Bur. Mines, Schedule* **14E** (1941).
[3] [filter-type dust, fume, and mist respirators], *U.S. Bur. Mines, Schedule* **21** (1934).
[4] [supplied-air respirators], *U.S. Bur. Mines, Schedule* **19A** (1937).
[5] [nonemergency gas respirators], *U.S. Bur. Mines, Schedule* **23** (1944).

with a suitable supporting harness. A check valve in the canister and an exhalation valve in the facepiece control the direction of flow of air through the device. The air-purifying materials in the canister vary with the type of canister since no one substance will remove all contaminants. Alkaline materials such as Caustite and soda lime combine with and remove any of the acid gases except nitrogen oxides; silica gel and activated carbon adsorb organic vapors; ammonia is removed by various materials such as silica gel adsorbent, or some other substance that has been impregnated with copper or cobalt salts to combine with the ammonia; while carbon monoxide is catalytically oxidized to carbon dioxide by Hopcalite, a trade preparation of manganese and copper oxides. Filters may be provided within the canister for removal of particulate matter. The protection that a canister provides determines its type, and depends upon the material with which it is filled. It may be for a single gas, one or more classes of gases, or for all gaseous contaminants. The types of canisters are designated by letters and a color code, as listed in Table 1.

TABLE 1

Color Code for Canisters

Canister type	Contaminants to be protected against	Colors
A	Acid gases	White
B	Organic vapors	Black
C	Ammonia	Green
D	Carbon monoxide	Blue
AE, BE, etc.	Dusts, fumes, mists, fogs, and smokes in combination with any of the above gases or vapors	½ in. contrasting black or white stripe (on the respective color)
AB	Acid gases and organic vapors	Yellow
ABC	Acid gases, organic vapors, and ammonia	Brown
N	All of the above atmospheric contaminants	Red

The canister gas mask is emergency equipment and is not suitable to wear for prolonged periods of work, because of discomfort and fatigue due to the resistance to inhalation and exhalation. This type of respirator is approved for use in concentrations of acid gases and organic vapors up to 2 per cent by volume, and in up to 3 per cent ammonia. The service life of a canister depends upon the concentration of gas encountered, the volume of air inhaled by the wearer, the characteristics and amount of the chemical absorbents, and other factors. Obviously the universal type of canister must be filled with a variety of materials in order to protect against practically all gaseous contaminants. For protection against a single known gas, or class of gases, a single-absorbent type of canister is preferable in that it has a longer life and provides more economical protection. The useful life of the universal, type N, canister is limited by the life of the drying agents used to protect the catalyst from moisture (2 to 6 hours). Figure 1 diagrams a typical type N canister. The continued use of a partially exhausted canister may be permissible in gases or vapors having distinct warning characteristics, provided it is used near an uncontaminated area, when the wearer may reach safety quickly after detecting leakage, because the

end of the useful period is not sharp, but rather gradual. Any used canister should always be replaced with a new one before the mask is used in an unusually hazardous situation.

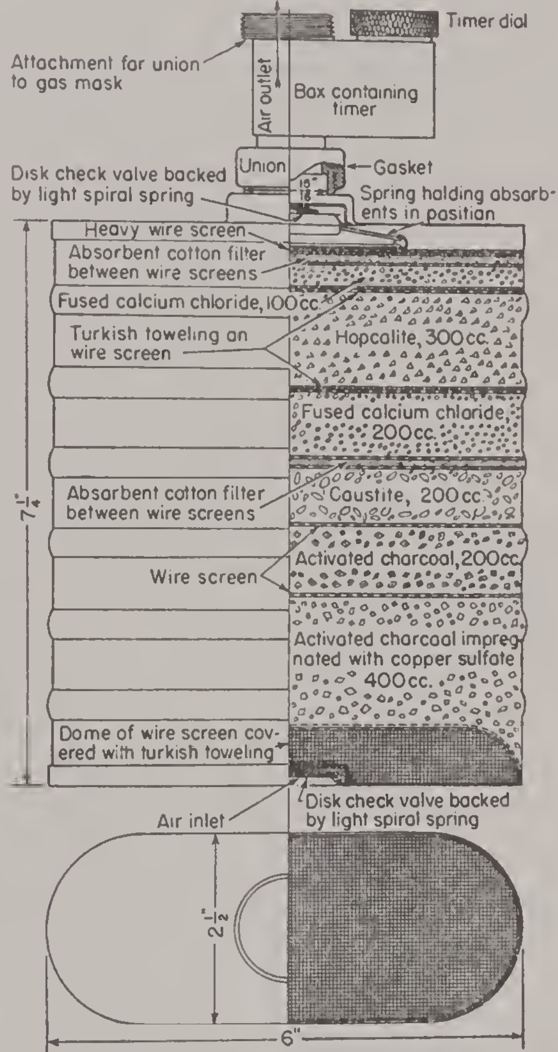

Fig. 1. A type N canister (*courtesy U. S. Bureau of Mines*).

2. Chemical Cartridge Respirators

Chemical cartridge respirators usually consist of a small canister attached directly to a half-mask facepiece. The fills are similar to those used in gas masks, and in fact these respirators may be considered miniature gas masks. Filters for removing particulate matter may be incorporated. These respirators are designed for prolonged use in light exposures where workmen could work without protection, but where prolonged daily exposures might prove harmful to health. The maximum

concentration of gases or vapors for which such devices are approved is 1000 p.p.m., 0.1 per cent by volume. Only a relatively few chemical cartridge respirators have been granted approval certificates, and the protection afforded by some of the unapproved articles is open to question. Recently, cartridge respirators have been approved for use against solvent vapors. A word of caution should be given, however, that these do not protect against lead mists, often associated with solvent vapors in paint spraying. Where lead mists are involved no cartridge respirator is approved, nor should any be depended upon; until further advances are made some air-supplying device is required. Respirators approved for removal of lead mists as well as solvent vapors and mists have not yet appeared.

3. Mechanical Filter Respirators (for Dust, Fume, Fog, or Mist)

Mechanical filter respirators usually consist of a fibrous filter, such as felt or specially treated cellulose fiber paper, secured in a holder and connected directly to a half-mask facepiece. The filter is a maze of fine, closely packed fibers that form a network of microscopic passages. When air is drawn through this maze, the major part of the suspended dust, fume, mist, and fog is removed by physical trapping. These filters are approved for various uses, but not all of them are suitable for every purpose. Filters approved for silica dusts, however, are suitable for all fibrosis-producing and nuisance dusts. Filters approved for mechanically generated lead dusts are suitable for other mechanically generated dusts: toxic, fibrosis-producing, or nuisance. None of these is suitable for metal fumes which, owing to their smaller particle size, require a finer mesh filter. Fumes, it must be understood, are particulate matter formed by volatilization and condensation, as for instance in lead burning, and must not be construed to be gases or vapors. A filter suitable for metal fumes will filter out any particles for which any mechanical filter is approved. Unlike the gas mask, the mechanical filter improves in filtering efficiency with use or plugging. Increased breathing resistance is the factor that limits this filter's life. These devices are intended for prolonged use and therefore are light in weight and compact. They do not seriously interfere with most ordinary duties. To say that they are comfortable is stretching the imagination, and where control by other means is feasible, control by personal respiratory protection is not the method of choice. Rather, mechanical-filter respirators are to be considered as either temporary or last-resort measures; but they certainly are to be recommended for any workman who is obliged to work in an atmosphere significantly contaminated by dust, fumes, fogs, or mists, especially if the contaminant is recognized as harmful to health.

B. ATMOSPHERE-SUPPLYING RESPIRATORS

Atmosphere-supplying respirators are independent of the wearer's atmospheric environment, and they offer protection in any atmosphere successfully withstood by the skin. There are two classes: one that supplies air through a hose or tube, and, the other, a self-contained type in which either a compressed oxygen or air supply is carried by the wearer or oxygen is generated as required.

1. Supplied-Air Respirators

Air-supplying respirators are further divided into three classes: hose masks, air-line respirators, and abrasive-blasting respirators.

Hose masks. Hose masks, type A supplied-air respirators, consist of a full facepiece, a harness, a 1-in. inside-diameter noncollapsible hose line securely fastened to the harness, and connected by a breathing tube, or tubes, to the facepiece, and a hand-operated blower. The harness and hose are strong enough to be used to retrieve the wearer in an emergency, and the maximum approved length of hose is 150 ft. The reason for requiring a hand-operated, rather than a motor-operated, blower is the additional safety factor of having a second man present in the event of any difficulty. The hose, blower, and check valve are such that the wearer can breathe without encountering excessive resistance to air flow, even though the blower is not operated: as for instance during the short time required to escape to pure air, if the second man should stop operating the blower. The blower intake must be located in uncontaminated air and, since approval is limited to from 25 to 150 ft. of hose, the device cannot be used more than that distance from respirable air. Air is supplied to the mask at a pressure equal to the very slight resistance of the exhalation valve, and therefore there is no resistance to inhalation while the blower is operating. A hose mask may be worn for a greater length of time without fatigue than can a canister gas mask. Type A hose masks are designed to be worn in atmospheres that are immediately dangerous to life, and to afford respiratory protection in all types of atmospheric contaminants, as well as in atmospheres deficient in oxygen. Special, or type B, hose masks, which are intended for nonemergency use, are similar to the type A described above except that they have no blowers, and some of the parts are lighter. These hose masks are approved with 25 to 75 ft. of hose, which terminates in a funnel fitted with a 100-mesh screen. This device should not be used in atmospheres immediately dangerous to life.

Air-Line respirators. Air-line, or type C, supplied-air respirators usually consist of a compressed-air supply system; a hose of relatively small internal diameter; a detachable coupling; an air-flow control valve, or orifice, that cannot be adjusted to an air flow of less than a specified minimum; and either a full or half-mask facepiece, helmet, or hood. The compressed air should be delivered through a trap and filter, if necessary, to make certain that it is not contaminated with rust, oil mist, or water. If the air is supplied by a piston-type compressor, some safeguard should be used to prevent its accidentally overheating and oxidizing the lubricant with the formation of carbon monoxide. A thermal cutout located at the exhaust port has been proposed for this purpose. This respirator gives protection from all contaminants, but its safe usage is limited to situations that are not immediately dangerous to life, from which the wearer can escape without the use of a mask. When a half-mask facepiece is used leakage around it is possible; also, there is no provision for breathing respirable air in the event of failure of the air supply.

Abrasive-Blasting respirators. Abrasive-blasting respirators are either of the above supplied-air respirators modified by the addition of a suitable covering to protect the head and shoulders of the wearer against impact and abrasion by rebounding abrasive material.

2. Self-Contained Air- or Oxygen-Supplying Equipment

The most common respiratory protective devices for supplying oxygen are self-contained oxygen-breathing apparatus, available in ½-, 1-, and 2-hour sizes. This apparatus consists of a cylinder of compressed oxygen, a reducing valve, an admission valve, a breathing bag, breathing tubes and mouthpiece with valves to control the direction of flow of inspired and expired air, a regenerator box containing an absorbent for removing carbon dioxide, and a cooling chamber. The entire device, which operates on a closed-circuit principle independent of the environmental atmosphere, is worn by the user. When the apparatus is adjusted, and the cylinder valve opened, oxygen flows in turn through reducing and admission valves into the breathing bag until its expansion releases a spring that closes the admission valve. As oxygen is breathed from the bag, the exhaled air is passed through the absorbent in the regenerator, then through the cooler, and back into the bag. Whenever the bag tends to collapse, its weight opens the admission valve, replenishing the oxygen supply in the bag.

The self-contained oxygen-breathing apparatus is approved for use only with mouthpiece and nose clips, and therefore requires gastight goggles when used in irritant gases. Even though this is not approved practice, it has been frequently and safely used with a modified gas-mask facepiece in certain situations. This apparatus protects the wearer against atmospheres deficient in oxygen, as well as from contaminants immediately dangerous to life. However, in the use of this device as well as the hose mask, the wearer is limited by what the skin will endure either from the standpoint of irritation or absorption—for instance, in atmospheres containing hydrogen cyanide. The oxygen-breathing apparatus is the heaviest respiratory protective device, and is a rather complicated mechanical apparatus. It requires training and experience in its use and maintenance, and it is important that the wearer have a clear understanding of its mechanical parts before attempting to wear it into an immediately dangerous atmosphere. Since all state codes, and the ASA code covering approved respiratory protective devices, are based upon the results of the approval tests of the United States Bureau of Mines, it is logical to be guided by the current list of approved devices from the Bureau.[6]

3. Newly Developed Air- or Oxygen-Supplying Devices

New and somewhat simplified self-contained air- or oxygen-supplying devices utilizing compressed air or oxygen, as well as self-contained oxygen-breathing ap-

[6] *List of Respiratory Protective Devices Approved by the Bureau of Mines*, obtainable currently from the U.S. Bureau of Mines, 4800 Forbes St., Pittsburgh 13, Penna.

paratus having potassium peroxide regeneration cartridges to supply oxygen and remove carbon dioxide, have found useful application. Each cylinder or canister for these devices is approved for either 30 or 45 minutes use. These devices are simplified and more adaptable to certain industrial uses than are the conventional type. However, they require training and experience for their safe use and should never be considered as either foolproof or as simple as a gas mask.

C. UNAPPROVED EQUIPMENT

There are many unapproved devices offered for sale to be used in many situations, but before selecting one of these devices it is well to consider the responsibility involved. If a respiratory protective device is proposed as a means of preserving health, or of saving a life in the event of an emergency, it is not something one can take chances with in order to save a few cents, or to oblige a favorite salesman. If the atmospheric contaminant is harmful, or suspected of being harmful, and United States Bureau of Mines approved respiratory protective devices are provided, there is evidence of an attempt to protect the health of the persons involved; but if unapproved devices are provided, negligence might be inferred. Few employers are in a position to establish the efficiency of respiratory protective equipment by dependable experimentation, and in the main they are therefore dependent upon outside advice. To use unapproved equipment in industrial situations is to assume the role of guinea pig to find possible shortcomings.

1. Filtering Efficiency against Paint Mist

The percentage collecting efficiency of a respirator is perhaps not of as much interest as is the amount of contaminant passing through the filter under various circumstances, because the amount passing through the filter determines the extent of a workman's exposure. It is only fair to state that practically any mechanical filter arrangement will remove some particulate matter from the air passing through it. Where the exposure is a borderline one, that is, near or only slightly above accepted "safe" practice, a device of low efficiency may lower the exposure to within accepted limits. This is, of course, not true of gases or solvent vapors, as these are not affected by mechanical filters. Table 2 indicates the filtering efficiency of some unapproved respirators in restraining lead in paint-spray mist.[7] The tests upon which the table is based were conducted for approximately one-half hour at an air flow of 32 liters per minute.

Although each of these materials has an efficiency of 74 per cent or better, none approaches the requirement of delivering air having less than 0.15 mg. lead per cubic meter of air. These tests indicate that even a layer of absorbent cotton between cheesecloth may remove 90 per cent or more of the lead pigment in paint mist. For an isolated short exposure with no other protection available, this would be worth while. However, when a workman is exposed to a mist containing, say, 350 mg. lead per cubic meter, his exposure through the respirator would still be over 100 times

[7] S. H. Katz, E. G. Meiter, F. H. Gibson, *U.S. Pub. Health Service Bull.* No. 177 (1928).

TABLE 2

Filtering Efficiency of Respirators in Paint Mist

Filter material	Resistance (inches of water) to air flow at 85 l./min.		Lead, mg./cu. m. in air		Filtering efficiency percentage
	Before test	After test	Before filter	After filter	
Sponge	0.3	0.3	395	63	84.0
Paper *a*, 1 ply	1.0	1.6	397	10.7	97.3
Paper *b*, 1 ply	0.2	0.6	374	15.0	96.0
Paper *b*, 2 plies	0.5	0.9	353	6.0	98.3
Gauzy tissue paper, 4 plies	0.5	0.8	498	39.8	92.0
Cotton flannel, 2 plies	0.2	0.4	458	22.9	95.0
1-ply silk, 3-ply cheesecloth	0.05	—	450	117.0	74.0
Cotton wool between cheesecloth	0.2	0.2	351	21.1	94.0
Charcoal cartridge with 20 plies of gauzy tissue paper	3.5	4.4	524	1.6	99.7

that of accepted safe practice. Obviously, percentage efficiency is not an acceptable means of rating respirators. The significant factor is the amount of leakage through the filter and such is now used in respirator testing for United States Bureau of Mines approval. In general, filters are less efficient against silica sprays and silica dusts than against lead, and the protection afforded against silica by many unapproved respirators is not of a high order.

2. Unreliable Carbon Dioxide Absorbents

Although the soda lime presently used in respirators to neutralize acid gases is not adversely affected by organic vapors, some alkaline absorbents used in the past as fills for gas-mask canisters, and for cartridges used in absorbing carbon dioxide in oxygen-rebreathing apparatus are known to have become paralyzed or poisoned by the vapors of ethyl alcohol. This was verified by experimental work in which carbon dioxide, passed through the granular absorbent, was absorbed completely until ethyl alcohol vapor was also introduced, whereupon the carbon dioxide passed through unchecked. After the ethyl alcohol was removed by aeration, the alkaline absorbent again reacted with carbon dioxide in a normal manner. The use of this and similar alkaline absorbents may have resulted in adverse experience with some of the earlier types of oxygen-rebreathing apparatus, when worn by members of mine rescue teams after they had partaken of alcoholic beverages.

III. Selection of a Respirator

In the selection of a respirator careful consideration should be given the chemical, physical, and toxicological properties of the contaminating material; possible secondary or by-products that may occur; whether the exposure is immediately dangerous, or whether injuries might arise only after prolonged exposure; the nature and amount of work to be done by persons wearing devices; whether the exposure will be brief or prolonged; whether sufficient consideration has been given to other

possible control measures. The person making the selection should know the principles, design, scope, use, limitations, advantages, and disadvantages of the respiratory protective equipment available.

Desirable qualifications of a respirator are: low resistance to inhalation and exhalation, smallest possible dead-air space, long service life, least interference with movement and vision, light construction, ruggedness, dependability, and low cost. The two factors that most influence fatigue are resistance to inhalation and exhalation, and the size of the dead-air space. Resistance to breathing is tiresome to muscles that are not trained to the effort; especially is this true of exhalation, which is normally passive. Excessive resistance can cause serious irregularities in respiration in untrained persons.

The dead-air space, space between the facepiece and the wearer's face, serves to enlarge the approximately 150 ml. normal space intervening between respiratory tissue of the lungs and the environmental atmosphere. The air in this space is partly depleted of oxygen and rich in carbon dioxide, and when the volume of the space is unnecessarily large, disturbances of respiration may result.

TABLE 3

Typical Situations and Suitable Respiratory Equipment

Environment necessitating protection	Respirator						
	Dust, mist, or fume	Chemical cartridge	Gas mask	Air-line	Hose mask	Abrasive-blasting	Oxygen-breathing apparatus
Abrasive blasting							
Dust, inside cabinet	−	−	−	−	−	++	−
Dust from leaks, outside cabinet	++	−	−	−	−	−	−
Asbestos workers	++	−	−	±	−	−	−
Dusts from grinding, buffing, polishing, sweeping, screening, shoveling, mining, tunneling, and stone cutting	++	−	−	+	−	−	−
Fires in chemical plants or involving high concentrations of toxic gases	−	−	+	−	±	−	++
Fires in dwellings, offices, or factories	−	−	++	−	±	−	+
Fumigation	−	−	++	−	++	−	+
Metal fumes from soldering, brazing, welding, flame cutting	++	−	−	++	−	−	−
Metalizing	+	−	−	++	−	+	−
Mine fires and explosions	−	−	+	−	−	−	++
Paint spraying	+	+	−	++	−	−	−
Oil-storage tanks (crude)	−	−	−	−	++	−	±
Refrigeration plant							
Leaks in ammonia lines (large)	−	−	−	−	++	−	+
Leaks in ammonia lines (small)	−	−	++	−	+	−	−
Sewers, wells, silos, unventilated holds of ships	−	−	−	−	++	−	+
Sour crude oil in ventilated areas	−	−	++	−	+	−	−
Toxic gases							
Less than 2 per cent	−	−	++	−	++	−	−
More than 2 per cent	−	−	−	−	++	−	+
Vats for beer, wine, vinegar, etc.	−	−	−	−	++	−	+

− Not suitable   + Some application   ++ Usually preferred

It is essential that the provision of respirators be under competent supervision; and that not only the correct respirator be provided, but that it be clean, sterilized, and maintained in good condition, and that the wearer be properly instructed in its purpose, use, and care.

IV. Cleaning and Sterilizing

When respirators have been worn several hours, they should be scrubbed with warm water and soap, and if they are to be given to another person they should first be sterilized. Several disinfecting solutions including 70 per cent alcohol have been used. Care must be exercised that the agent chosen does not damage any part of the device, and that, if it is an irritant or sensitizer, the last traces be washed off before the respirator is returned to use. Where doubt exists, the manufacturer of the device should be consulted regarding possible adverse effects of a proposed sterilizing agent on his product.

V. Examining a Respirator

First determine whether the device has been approved for the purpose planned. See whether the rubber parts are pliable and in good condition. Examine the valves and test for tightness as described below for facepiece and breathing tubes. Check the breathing resistance by machine (manometer reading at measured air flow) or by putting it on. If the device is to be worn in an immediately dangerous atmosphere check the facepiece and breathing tubes for tightness by putting the mask on, closing off the air inlet, inhaling and holding the breath for about ten seconds, during which time the facepiece should remain collapsed. Filters or canisters should be examined and replaced where necessary. In making a decision as to the need for replacement two facts are of most help: first, the amount of resistance offered to breathing through the device when it is put on in normal air; second, the record of date of purchase and time of actual usage in contaminated air, which should always accompany each canister. Mechanical filters that do not offer excessive resistance to air flow and are obviously intact may be considered to retain their original efficiency—in some cases to have improved it—and therefore do not need replacing. Canisters may need replacing if the resistance has become too great from any cause, such as corrosion, caking of chemicals, etc. Canisters may likewise need replacing if the efficiency of the material within them has been depleted, as by chemical exhaustion due to old age or too much usage. If uncertainty exists, yet it is desired to use the canisters, they may be tested by inhaling through them some relatively harmless gas having chemical properties and reactions similar to the gas or vapor in which the device is to be used. An odorous or irritant, relatively innocuous, material of the class against which the device is designed to protect may be used to make a test atmosphere and the device tried out in it before being used in dangerous situations. As pointed out previously, canisters for protection against carbon monoxide are not reliable and should not be used for this purpose after about two hours actual use, even though their appearance may be good.

CHAPTER FIFTEEN

Dust and Its Role in the Causation of Occupational Disease

EDWARD E. DART, M.D.

I. Introduction

The industrial hygienist and the industrial physician are concerned with dust because of its almost constant dispersion in air, where it may be inhaled and in some instances cause disease. This suspension of finely divided particles in the air may not ordinarily attract attention in rural areas but the smokiness of large cities is immediately apparent. Clean country air may contain as much as 0.2 mg. dust per cubic meter of air, whereas the average amount in city air during the winter months is approximately 0.5 mg. per cubic meter of air.[1] Thus, the cloud of dust that arises from a stonecutter's chisel is an excessive amount superimposed on that which is present in the already dust-laden air.

In addition to the medical problems, the legal entanglements which may revolve around dustiness are often of sufficient complexity that months of careful study are required to determine or fix responsibilities. In cities where general industrial smoke contamination is a perennial problem individual firms may be selected each year to bear the brunt of civic ire, and each year certain luckless corporations are forced to defend themselves in civil suits that are based almost entirely upon claims having no factual evidence for support. Medical-legal situations may be even more complex than the nonmedical problems and are complicated by numerous intangible factors. Not only does the exact nature of the disease and its relation to dust require proof, but the actual source of exposure must be determined so that a nondusty industry will not be held responsible for dust disease that may have resulted from exposure many years prior to the onset of the disease.

This chapter is written as an attempt to bring together facts necessary for a general understanding of dust and dust diseases. The presentation in the first portion is somewhat general so that the contents can be readily grasped by physicians with-

[1] J. M. DallaValle, *Micromeritics. The Technology of Fine Particles*, 2nd ed., Pitman, New York, 1948.

out an extensive background in engineering or physics, and by engineers and industrial hygienists without medical training. In the later sections an attempt is made to review pneumoconioses in sufficient detail to aid the physician called upon to examine employees whose work exposes them to dust.

A. PROPERTIES OF DUST

The important physical and chemical properties of dust have been summarized by Drinker and Hatch,[2] and much of the material presented here was obtained from that source.

(*a*) *Settling rates.* Suspended microscopic dust particles are attracted to the earth by gravity just as is any other free body. However, because of their small mass and the relatively great resistance of the air, they do not fall according to the usual laws of gravity. Settling rates are much greater for large than for small particles. A settled dust, accordingly, may contain a proportionately greater percentage of large particles than the contaminated air from which it settled and in which the fines predominate. Ore as it is found in mines may contain a certain amount of quartz, which is frequently harder than the other minerals present. Because of this relative hardness the quartz may be ground less finely in drilling operations. Much of this coarser quartz dust may settle out from the air in the working area with comparative rapidity, leaving a smaller percentage of quartz in the atmospheric dust than may be present either in the parent material or in the settled rafter dust.

(*b*) *Flocculation.* Dust produced by crushing or grinding a material such as quartz differs from fume such as magnesium oxide in respect to its tendency to flocculate. Freshly formed fume particles are usually well below 0.3 μ and accordingly exhibit marked Brownian movement. Because of this and perhaps other factors, they tend to collide and form flocs which, because of their larger size, settle out relatively quickly. Such masses tend to adhere to vertical walls and projecting surfaces.

True dust is much less apt to flocculate than is fume, and any flocs formed are much more loosely bound together. Settling of dust clouds is therefore much less pronounced than is settling of fume clouds. As a dust cloud clears, the size of the particles remaining in suspension decreases and the degree of dispersion increases, i.e., the ratio of flocculated to discrete particles becomes less. On the contrary, in a metallic fume both the percentage of flocs and their size increase with the age of the cloud.

Turbulence in the air increases floc formation in fume clouds by increasing the collision frequency, but it does not improve the settling rate of dust.

Humidity below saturation is said to have little effect on flocculation time. However, humidity to the point of supersaturation is an important factor, as the dust particles function as nuclei on which water may condense, thus increasing particulate size.

(*c*) *Wetting.* Wetting is primarily an adsorption phenomenon in which the

[2] P. Drinker and T. Hatch, *Industrial Dusts.* McGraw-Hill, New York, 1936.

surfaces of the particles become covered with a film of water. Most liquids tend to spread on plane surfaces, but great force must often be used to wet dust, probably because the particles are already surrounded by a film of air. Wetting is of importance in dust sampling and in control of dust.

Three factors have been described by Drinker and Hatch as of importance in the wetting of dust. First, it is necessary to maintain intimate and vigorous contact of long duration between the dust and liquid. Second, it is advantageous to apply the liquid immediately at the dust source, because the heat usually generated in producing dust by drilling or grinding hampers air adsorption and because continuous flooding at the source excludes air. Third, wetting agents may be used to increase the wetting power of water.

(*d*) *Electrical properties.* Dust particles are electrically charged and accordingly are attracted to oppositely charged particles. If, therefore, particles in a dust suspension are given an electrical charge, the tendency for floc formation should be increased. Attempts have been made to utilize electrically induced flocculation as a method of air purification but without great success. Electrostatic precipitation, on the other hand, has been used quite successfully for collection of dust and fume, but such precipitation depends upon the attraction of the electrically charged particles to an oppositely charged plate rather than upon flocculation.

(*e*) *Optical properties.* Dust or moisture particles reflect light and it is this light, reflected from dust particles otherwise too small to be seen, that makes them visible when a beam of light enters a darkened room. The scattering of a beam of light by dust or mist is known as the Tyndall phenomenon. The optical properties of suspended particles in air vary with their shape, their transparency, and especially their size. With particles larger than the wave length of light (about 0.7 μ), the strength of the Tyndall beam varies directly with particle surface area and concentration; thus, for a given weight concentration it varies inversely with the particle size. Attempts have been made to utilize these optical properties in the measurement of dust concentration, but variation in the size of the particles makes such determinations unreliable.

B. ATMOSPHERIC DUST CONCENTRATIONS AND PARTICLE SIZE

Whenever a solid or liquid is ground or broken into particles as small as dust, the surface area is greatly increased. Thus if a cube of mineral 1 cm. in each of its dimensions is ground into small cubes 1 cu. μ in size, there will be 10^{12} particles with a total surface area of 6 sq. meters as compared with 6 sq. cm. for the original cube. This great increase in surface area is largely responsible for the increased chemical activity of finely ground materials and may be an important factor in the production of silicosis.

Industrial dust concentrations may range from the amounts present in "pure air," in operations where no dust is produced or where there is adequate dust control, to as high as 2 billion particles per cubic foot of air, in rock drilling. DallaValle[1] has pointed out that more than 50 per cent of industrial dusts are greater than 1 μ in

size while in atmospheric dust the median size is approximately 0.5 μ. Bloomfield[3] found that only 20 per cent of the particles found in air in fifty industries were smaller than 1 μ and that the median size was 1.3 μ; he suggested that most of the particles of smaller size found in industrial atmospheres were those normally present in air. In certain industries, however, such as pneumatic rock drilling, large numbers of particles well below 1 μ in size are produced.[4]

II. Classification of Dust Based on Its Effect in the Body

The industrial hygienist is interested in dust because of its effect on the human body. Therefore, a limited classification of dust from this viewpoint may form a basis for relating the chemical composition of dust to the anatomical and physiological reactions which occur in injury from dust.

(1) Dust causing extensive pulmonary fibrosis. This group includes all dust containing free silica or asbestos. Free silica is encountered in nature in the following forms: *quartz*—a crystalline form found in granite, schist, quartzite, sandstone, and sand; *opal*—an amorphous colloidal hydrate found in diatomaceous earth; *flint*—a crystalline form found free or in association with chalcedony; *chalcedony*—a mixed form consisting of fibers of quartz and an *interstitium* of opal. Other less common forms are tridymite, cristobalite, and siliceous or vitreous glass. *Asbestos* is hydrated magnesium silicate. It is mined in Canada as the mineral chrysotile.

(2) Dust causing minimal pulmonary fibrosis or no fibrosis. This group includes almost all inorganic dust except that containing free silica or asbestos. To the industrial hygienists the silicates, carbon, iron, and barium are the most important forms of dust in this group—the silicates because of their close chemical relationship to free silica, carbon because of its frequent occurrence in industrial atmospheres and its tendency to accumulate in the lungs, and iron and barium because of the unusual roentgenographic findings produced.

(3) Dust causing chemical irritation. This group includes obvious chemical irritants such as acids, alkalies, fluorides, and chromates. (Fluorides may also be included in group 4.)

(4) Dust causing systemic poisoning. This group includes dust of certain metals such as lead, arsenic, drugs, and all systemic poisons that may occur in dusty form.

(5) Dust causing allergic manifestations such as dermatitis, hay fever, and asthma. This group includes almost innumerable organic dusts such as pollens, synthetic resins, plastics, felt, fur, gums, kapok, leather, spices, tobacco, paper, rags, rayon, rosin, rubber, wood dust, starch, and wool. In addition to causing dermatitis and other allergic manifestations, these dusts may irritate the skin and mucous membranes by purely mechanical means.

(6) Dust causing a febrile reaction (acting in an unknown manner, possibly as an

[3] J. J. Bloomfield, *U.S. Pub. Health Repts.*, **48**, 961 (1933).
[4] T. Hatch and C. L. Pool, *J. Ind. Hyg.*, **16**, 177 (1934).

allergen). The two outstanding members of this category are metal fume (especially zinc oxide) and cotton dust.

III. Anatomical Factors of Importance in Injury by Dust

The fate of inhaled dust in the body can be understood only by knowing something of the anatomical structures and physiological reactions involved in respiration.

The air passageway consists of the nose, pharynx, trachea, bronchi, bronchioles, and alveoli. The relationship of these various structures is shown in Figure 1.

(*1*) *Nose.* The portions of the nasal cavities just within the external nares are lined with skin containing hairs. The remaining parts of the nasal cavities are lined with mucous membrane, composed on its surface of ciliated and mucus-secreting cells. This tissue is highly vascular and contains freely anastomosing venous channels. The nasal passages are connected directly with the air sinuses in the skull.

The hairs in the entrance of the nose and the mucous material secreted by the lining membrane collect many of the larger inhaled particles. The cilia of the entire respiratory tract tend to move material toward the mouth, those of the nose tending to force the mucus and particles in it toward the pharynx. An indication of the importance of the nose as a protective mechanism has been shown by G. Lehmann.[6] This investigator studied 426 miners, of whom 241 had silicosis and 181 were normal, and found the median efficiency of nasal filtering in the silicotics to be 27.5 per cent and in the normals 45 per cent. He concluded from this that persons who develop silicosis do so, in part at least, because of a faulty filtering mechanism in the nose.

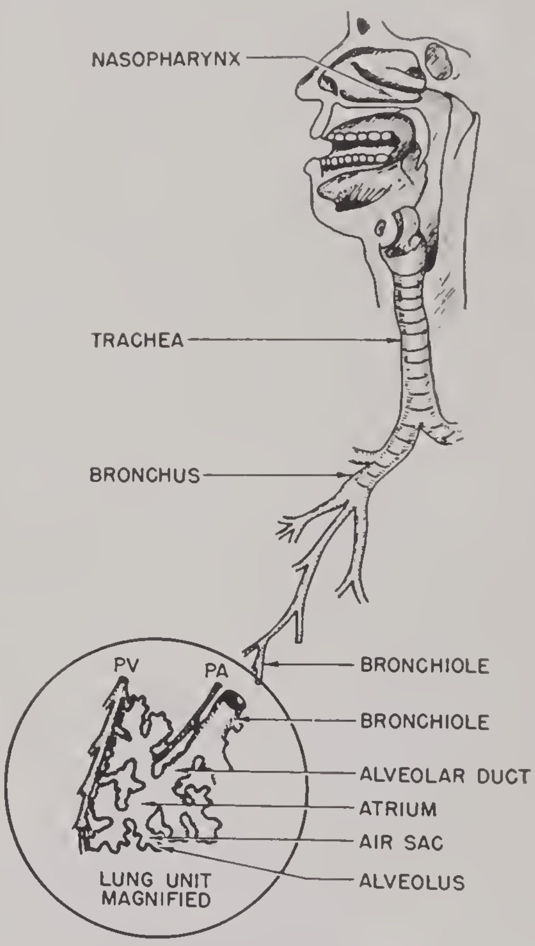

Fig. 1. Diagrammatic representation of the respiratory tract.[5]

(*2*) *Pharynx.* The pharynx is a common pathway for food and air, connecting

[5] L. E. Hamlin, *Rocky Mt. Med. J.*, **41**, 391 (June, 1944).
[6] G. Lehmann, *Arbeitsphysiol.*, **7**, 147 (1933); see also *J. Ind. Hyg.*, **17**, 37 (1935).

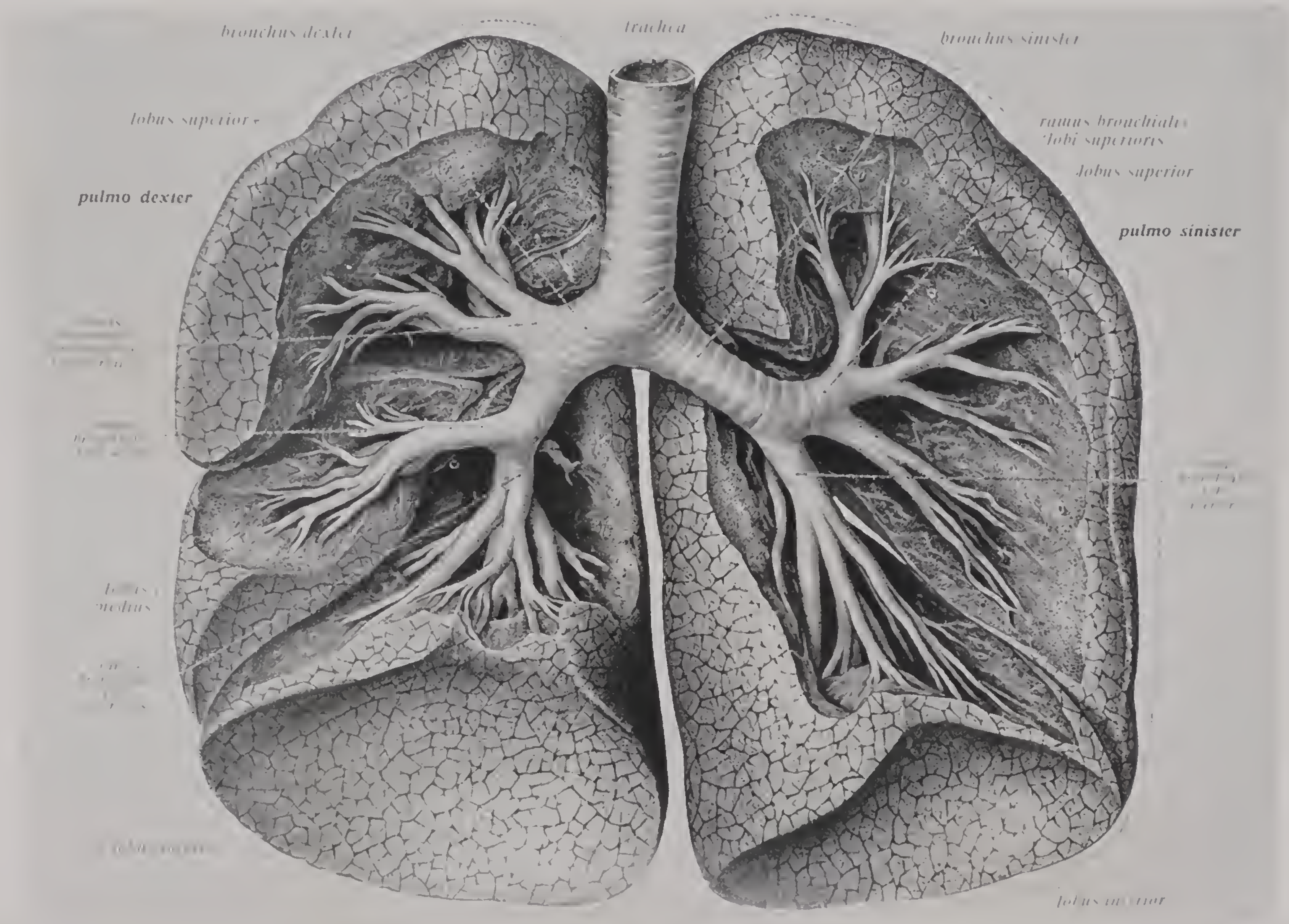

FIG. 2. The two lungs with the trachea and the branching of the bronchi exposed by removing portions of the lung substance.[7]

the nasal passage with the oral pathway and with the trachea. Its nasal portion is lined with ciliated epithelium.

(*3*) *Larynx and trachea.* The larynx lies between the pharynx and trachea. It is strengthened by strong cartilages, contains the vocal mechanism, and has at the opening to the oral passage a valvelike structure—the epiglottis—which closes the tracheal opening during swallowing to prevent food from entering the respiratory pathway. The trachea is a tube 1 to 2 cm. in diameter, strengthened by cartilage rings and, like the nasal pharynx, lined with ciliated and mucus-producing cells. The relationship of the trachea and bronchi to the lungs as a whole is shown in Figure 2.

(*4*) *Bronchioles and alveoli.* Macklin[8] divides the bronchial tree into two parts that may be compared to the trunk and branches of a tree. The first part, which extends from the trachea to the *terminal bronchioles* inclusive, serves simply as an air conduit, and, like the branches and twigs of a tree, has no respiratory function. The terminal bronchioles are the last of a series of subdivisions of these nonrespiratory bronchioles. The muscular tissue in their walls is more highly developed than that in any other part of the bronchial tree and when fully contracted exerts a sphincterlike action which can completely shut off the air supply to the chambers beyond.

The structures lying distal to the terminal bronchioles are the "leaves" of the bronchial tree. They have a respiratory function: the interchange of gases between air and blood occurs through their walls. The respiratory portion consists of the respiratory bronchioles, alveolar ducts, alveolar sacs, and pulmonary alveoli. The cluster formed by a related group of these structures constitutes a *lung unit* or *primary lobule*. This is the distensible or bellows part of the lung.

The *respiratory bronchiole* as described in Best and Taylor[9] has the same diameter as the terminal bronchiole, of which it appears as a branch or a continuation. Five or six *alveolar ducts* arise from each respiratory bronchiole. Each alveolar duct after a variable number of rebranchings gives rise to from three to six dilatations, the *alveolar sacs*. The bays in the walls of the latter constitute the *pulmonary alveoli*, which are lined by a single layer of flattened epithelial cells cemented together. The alveolar walls contain elastic fibers and a rich network of capillaries. Frequently a single capillary channel alone intervenes between the walls of adjacent alveoli. The blood in the capillaries is therefore separated from the air in the alveoli by only two membranes of the utmost delicacy—the alveolar and capillary walls, so the greatest freedom is afforded for the diffusion of gases from the blood to the alveolar air and from the alveolar air to the blood.

The bronchioles, as they approach the periphery of the lung, branch and rebranch repeatedly, diminishing in length with each subdivision. The first branchings

[7] J. Sobotta and J. P. McMurrich, *Atlas of Human Anatomy*. Vol. II. Stechert, New York, 1933.

[8] C. C. Macklin, *Am. Rev. Tuberc.*, **25**, 363 (1932).

[9] C. H. Best and N. B. Taylor, *The Physiological Basis of Medical Practice*. 3rd ed., Williams & Wilkins, Baltimore, 1943.

are about 1.5 mm. in length and from 0.3 to 0.4 mm. in diameter. The terminal and respiratory bronchioles are from 0.2 to 0.5 mm. in length but of about the same diameter as the more central subdivisions. That is, the bronchioles, though progressively shorter, show practically no decrease in diameter as they pass toward the periphery. The alveolar sac, however, is considerably wider than either the respiratory bronchiole or the alveolar duct from which it arises. The pulmonary alveoli are semiglobular and have diameters ranging from 0.075 to 0.125 mm.; the total number in the lungs has been estimated by Zuntz at 750 million. Willson[10] estimates the total epithelial surface of the lungs at 70 sq. meters; of this, probably 55 sq. meters, over 25 times the surface area of the skin, is respiratory.

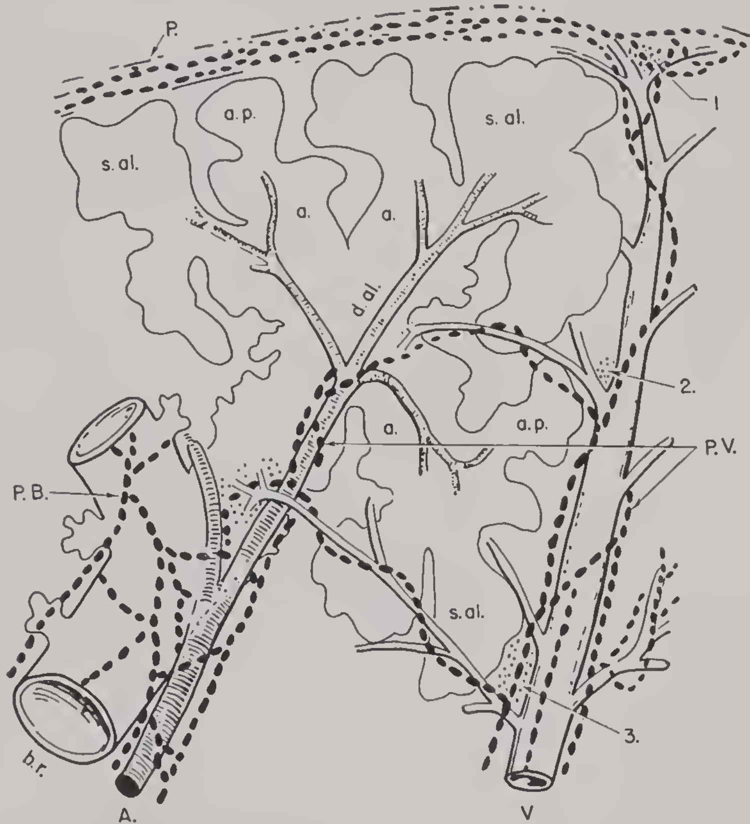

FIG. 3. Composite diagram (modified from Miller[11]) of the primary lobule lymphatic system, indicating the primary distributions or accumulation points for dust which will lead to predominant phases of pneumoconiosis: *b.r.*, respiratory bronchiole; *d.al.*, alveolar duct; *a.*, atria; *s.al.*, sacculi alveolare; *a.p.*, alveoli opening into respiratory bronchioles and alveolar ducts in close relation with the origins of peribronchial and perivascular lymphatics; *A*, branch of pulmonary artery, accompanying the air passages; *V.*, branch of pulmonary vein in interlobular septum; *P.*, pleura; *P.B.*, peribronchial lymphatics; *P.V.*, perivascular lymphatics; 1, 2, 3, and other dotted areas, lymphoid deposits. (By previous permission of Dr. W. S. Miller.)

[10] H. G. Willson, *Am. J. Anat.*, **30**, 267 (1922).

[11] W. S. Miller, as reproduced by Pendergrass in A. J. Lanza, *Roentgen Diagnosis, Silicosis and Asbestosis*, Oxford Univ. Press, New York, 1938.

From these facts it is apparent that lung tissue offers by far the best medium of any in the body for the absorption of materials that may come in contact with it.

(*5*) *Blood vessels and lymphatics.* Except in the alveolar areas the blood vessels and lymphatics follow rather closely the path of the bronchial tree. The relationship in the periphery of the lung is shown clearly in Figure 3.

The lymphatic system consists of vessels that carry fluid similar to the blood plasma and nodules composed largely of protective and phagocytic cells. The lymphatic vessels and lymphoid tissue are important in connection with a study of dust because most of the dust particles finally lodge in the peribronchial and interstitial lymphoid tissues, carried there by wandering phagocytic cells.

(*6*) *Phagocytes.* In the alveolar spaces there are large cells capable of ingesting foreign material and having the power of independent motion. A large number of these ameboid forms appear wherever foreign material enters the lungs. After ingesting the exogenous particles, some of these cells pass into the blood stream and finally lodge in the spleen and liver or move elsewhere in the lung tissues; the majority, however, make their way to the lymph vessels and eventually to accumulations of lymph tissue, where they lodge. This resting place may be anywhere in the lung. Some phagocytes migrate peripherally to the pleura and others centrally to the hilus. In the lymph tissue the foreign material may be absorbed, may remain in an inert state, or may, by some chemical reaction, initiate pathological changes such as the formation of silicotic nodules.

IV. Physiological Factors of Importance in Injury by Dust

(*1*) *Volume of air inhaled.* Just as we are interested in the amounts of dust suspended in air, so are we also interested in the amount of air inhaled by men under different conditions. This has been discussed in Chapter 7.

(*2*) *Dust retention.* Before we can arrive at a logical basis for determining maximum permissible concentrations, it is necessary to know what proportion of inhaled dust is retained. Since most dust-collecting apparatus imposes considerable resistance to the passage of air from the lungs, satisfactory results were not obtained in such studies until Baumberger[12] used an electrostatic precipitator with tubes large enough to reduce the resistance to a negligible factor. His studies on tobacco smoke yielded results considerably higher than those obtained later by Sayers,[13] by Drinker, Thomson, and Finn,[14] and by Brown.[15] Baumberger found as much as 85 per cent retention of smoke. Sayers, working with tetraethyl lead in concentrations varying from 0.35 to 10.4 mg. per cubic meter of air, found that only 15 per cent was retained and attributed this limited retention to the small particle size. Brown's studies gave rather conclusive results, showing that the percentage retention is inversely proportional to the minute volume of air breathed and to the respiratory

[12] J. P. Baumberger, *J. Pharmacol.*, **21**, 47 (1923).
[13] R. R. Sayers, *U.S. Bur. Mines Repts. Investigations* No. **2661** (1924).
[14] P. Drinker, R. M. Thomson, and J. L. Finn, *J. Ind. Hyg.*, **10**, 13 (1928).
[15] C. E. Brown, *J. Ind. Hyg.*, **13**, 293 (1931).

rate, whereas it is directly proportional to the particulate size, density of the dust suspended in air, and the extent to which the dust is wetted while passing through water. He found that retention was not affected by volume per respiration, vital capacity, or relative humidity of inspired air.

V. Dust Causing Extensive Pulmonary Fibrosis (Silicosis and Asbestosis)

A. HISTORY

Since ancient times it has been thought that dust caused disease. Perhaps the earliest reference to disease caused by dust and fume is that of Plinius,[16] who described the devices used by refiners to prevent the breathing of "fatal dusts."

In 1556, in *De re metallica*, Agricola[17] stated:

"On the other hand, some mines are so dry that they are entirely devoid of water, and this dryness causes the workman even greater harm for the dust which is stirred and beaten up by digging penetrates into the windpipe and lungs and produces difficulty in breathing."

The best of the early writings on silicosis is that of Ramazzini,[18] translated in 1705 in *A Treatise of the Diseases of Tradesmen*, in which he stated:

"For in hewing marble or stones out of the rock, in polishing and cutting them, they oftentimes suck in by inspiration the sharp, rough and cornered small splinters or particles that fly off; so that they are usually troubled with a cough, and some of them turn asthmatick and consumptive . . . And in dissecting the corps of such artificers, the lungs have been found stuffed with little stones. Diemerbroek gives a curious relation of several stone cutters that dy'd asthmatick, and were opened by him; in whose lungs he found such heaps of sand that in running the knife through the pulmonary vesicles he thought he was cutting some sandy body. He adds that he was informed by a master stone cutter that in cutting stones there rises such a subtile dust, as is able to penetrate through ox bladders hung in the shop . . . And this very dust he took to be the cause of the death of many unwary workmen."

In recent years the contributions to knowledge of silicosis have been sufficiently substantial, numerous, and varied to make this perhaps the most widely discussed occupational disease. Silicosis is of particular interest to students of preventive medicine not only because of its general distribution in industry but more particularly because of its tendency to increase susceptibility to tuberculosis—a characteristic inherent in the disease. The limited space of this chapter does not permit reference to many sound contributions which have led to our present understanding of dust disease. An exceedingly interesting and somewhat detailed review of the history of diseases caused by dust may be found in the work of Lanza.[19]

B. EXPOSURE TO SILICA IN INDUSTRY

Since siliceous material makes up the bulk of the earth's crust, it is not surprising to find silica exposures in industry, where raw materials from the earth are used

[16] Caius Plinius Secundus, *Naturalis historia*, Bk. II. Trans. by K. C. Bailey under the title, *The Elder Pliny's Chapter on Chemical Subjects*, Pt. I. Longmans, Green, New York. 1929.

[17] Georgius Agricola, *De re metallica*, Bk. I. Trans. from 1st Latin ed. of 1556 by H. C Hoover and L. H. Hoover. Mining & Sci. Press, San Francisco, 1912.

[18] B. Ramazzini, *A Treatise of the Diseases of Tradesmen*, English trans., 1705.

[19] A. J. Lanza, *Silicosis and Asbestosis*. Oxford Univ. Press, New York, 1938.

to make many of the commodities necessary to our daily lives. Rocks and minerals are often intimately associated with free silica and it is obvious that those occupations concerned with mining, rock grinding, or drilling may constitute silicosis hazards, as well as occupations concerned with the processing and industrial use of siliceous products.

According to Knopf[20] the most common forms of free silica used industrially are massive crystalline quartz, quartzite, sandstone, flint, tripoli, diatomaceous earths and silica sand. Table 1, from Ladoo,[21] illustrates the great variety of uses to which silica is put in industry and indicates the kind of silica adapted to each purpose.

TABLE 1

Industrial Uses of Silica and Types of Silica Used[21]

Uses	Types
Abrasives	
In scouring and polishing soaps and powders.	Quartz, quartzite, flint, chert, sandstone, sand, tripoli and diatomaceous earth; all in finely ground state.
In sandpaper.	Quartz, quartzite, flint, sandstone and sand; coarsely ground and closely sized.
In sand-blast work.	Quartz, quartzite, sandstone and sand, crushed into sharp angular grains uniform in size.
Metal buffing, burnishing and polishing.	Ground tripoli and other forms of ground silica.
For sawing and polishing marble, granite, etc.	Sharp, clean sand graded into various sizes.
As whetstones, grindstones, buhrstones, pulpstones, oilstones, etc.	Massive sandstone from very fine- to moderately coarse-grained.
Tube-mill lining.	Chert, flint and quartzite in dense, solid blocks.
Lithographers' graining sand.	Medium to fine sand or rather coarsely ground silica and tripoli.
Tube-mill grinding pebbles.	Rounded flint pebbles.
In tooth powders and pastes.	Various forms of pure silica finely ground.
Wood polishing and finishing.	All forms of silica ground to medium fineness.
Refractories	
In making silica fire brick and other refractories.	Fairly pure quartzite known as gannister; not less than 97 per cent SiO_2 nor more than 0.40 per cent alkalies, tightly interlocking grains desired.
Metallurgy	
In making silicon, ferrosilicon and silicon alloys of other metals, such as copper.	Moderately pure sand, massive crystalline quartz, sandstone, quartzite or chert.
As a flux in smelting basic ores.	Massive quartz and quartzite.
Foundry-mold wash.	Ground sandstone, quartz and tripoli.
Foundry parting sand.	Fine sand and ground tripoli.
Chemical industries	
As a lining for acid towers.	Massive quartz or quartzite.
As a filtering medium.	Massive diatomaceous earth and tripoli, sand, finely granular quartz or quartzite, finely ground tripoli, diatomaceous earth and other forms of silica.
In the manufacture of sodium silicate.	Pure pulverized quartz sand, pure tripoli and diatomaceous earth.
In the manufacture of carborundum.	Pure quartz sand.

Table continued

[20] A. Knopf, *U.S. Pub. Health Bull.* No. **187** (1929).

[21] R. B. Ladoo, *Silica, Nonmetallic Minerals.* McGraw-Hill, New York, 1925, p. 525.

TABLE I (*continued*)

Uses	Types
Paint	
As an inert extender.	Finely ground crystalline quartz, quartzite and flint, also finely ground sandstone, sand and tripoli.
Mineral fillers	
As a wood filler.	Finely ground crystalline quartz, quartzite, flint, tripoli and other types of ground silica.
In fertilizers. In insecticides. As a filler in rubber, hard rubber, pressed and molded goods, phonograph records, etc. In road asphalt surfacing mixtures.	Finely ground silica of all types.
Ceramics	
In the pottery industry as an ingredient of bodies and glazes.	Flint, tripoli and chert, and other amorphous silica preferred; also all other forms of very pure silica, all finely ground.
In the manufacture of ordinary glass.	Pure quartz sand.
In the manufacture of fused-quartz chemical apparatus, such as tubes, crucibles and dishes.	Very pure massive quartz preferred.
Decorative materials	
In the manufacture of gems, crystal balls, table tops, vases, statues, etc.	Rock crystal, amethyst, rose quartz, citrine quartz, smoky quartz, chrysoprase, agate, chalcedony, opal, onyx, sardonyx, jasper, etc.
Insulation	
Heat insulation for pipes, boilers, furnaces, kilns, etc.	Massive and ground diatomaceous earth.
Sound insulation in walls, between floors, etc.	Massive and ground diatomaceous earth.
Structural materials	
Sand-lime brick.	Moderately pure, sharp, angular sand, preferably finer than 20-mesh, together with a small percentage of finely pulverized silica.
Optical quartz	
For the manufacture of lenses and accessories for optical apparatus.	Clear, colorless, flawless rock crystal or massive crystallized quartz.

C. ETIOLOGY OF SILICOSIS

Silicosis has been defined by the Committee on Pneumoconiosis of the Industrial Hygiene Section of the American Public Health Association[22] as:

"A disease due to breathing air containing silica (SiO_2), characterized anatomically by generalized fibrotic changes and the development of miliary nodulation in both lungs and clinically by shortness of breath, decreased chest expansion, lessened capacity for work, absence of fever, increased susceptibility to tuberculosis (some or all of which symptoms may be present) and by characteristic x-ray findings."

The definition adopted at the International Silicosis Conference in 1930 and reaffirmed at the 1939 conference is generally accepted and is somewhat simpler than the above. It is as follows:

[22] R. R. Sayers, *Yearbook, Am. Pub. Health Assoc.* (1932–33).

"Silicosis is a pathological condition of the lungs due to inhalation of silicon dioxide. It can be produced experimentally in animals."

Lanza[23] in "Etiology of Silicosis," as printed in the National Silicosis Conference Report on Medical Control, states:

"Simple or uncomplicated silicosis is a chronic, fibrotic disease of the lungs, due to the massive invasion of the pulmonary tissue by silica (SiO_2), inhaled in the form of dust. In its early stages, silicosis may be symptom free; in its later stages shortness of breath, decreased chest expansion, lessened capacity for work, may—one or more—be present, together with an increased susceptibility to tuberculosis. The disease presents the characteristic x-ray appearance of nodulation, without which a clinical diagnosis may not be made."

The production of silicosis depends upon the following factors: the composition of inhaled dust, the number of particles of inhaled dust, the size of the particles of inhaled dust, the length of time during which particles are inhaled, and individual susceptibility.

1. *Composition of Dust in Relation to Production of Fibrosis*

The fact that silicosis is caused by free silica (SiO_2) is attested by a great mass of clinical experience as well as by experimental observations. Gye and Kettle[24] have shown that silica in solution, or in noncrystalline form, stimulates the proliferation of fibroblasts in tissues. Gardner[25] produced a reaction in the lungs of animals in a period as short as two years by exposure to extremely high concentrations of dust. Miller and Sayers[26] developed an intraperitoneal injection technique for testing the tissue response to dust, and their method has been used extensively by the United States Public Health Service. On the basis of this procedure it has been found that all dusts behave in one of three ways in the body tissues; they may disappear (be absorbed), cause cellular proliferation, or remain inert in the tissues.

Dust Causing an Absorptive Reaction. No cases of pneumoconiosis have been reported and confirmed among workers exposed solely to dust of the absorptive group. In experimental animals this dust disappears, leaving little or no scarring. A list of different varieties of dust investigated, which are absorbed, follows. These are of industrial origin unless otherwise stated.

Calcite—essentially pure calcium carbonate.

Precipitated calcium carbonate—containing 10.1 per cent magnesium carbonate, 0.1 per cent magnesium oxide, 0.6 per cent iron and aluminum oxides and 0.4 per cent total silica.

Gypsum—the uncalcined, natural mineral composed essentially of calcium sulfate with 1.3 per cent total silica.

Limestone—not less than 82 per cent calcium carbonate, less than 12 per cent total silica, and not more than 10 per cent free silica.

Portland cement—containing 74.4 per cent calcium oxide and 21.1 per cent total silica. Free silica not reported.

Pyrolusite—composed of 54.9 per cent manganese with no quartz reported.

[23] A. J. Lanza, Report on Medical Control, National Silicosis Conference, *U.S. Dept. Labor, Div. Labor Standards, Bull.* No. **21**, Pt. 1 (1938).

[24] W. E. Gye and E. H. Kettle, *Brit. J. Exp. Path.*, **3**, 241 (1922).

[25] L. U. Gardner, in A. J. Lanza, *Silicosis and Asbestosis.* Oxford Univ. Press, New York, 1938.

[26] J. W. Miller and R. R. Sayers, *U.S. Pub. Health Repts.*, **56**, 264 (1941). Reprint 2234.

Dust Causing a Proliferative Reaction. Each type of dust examined that falls into the proliferative group is known to produce nodular, pulmonary fibrosis and each is a form of free silica. In experimental animals such dust produces nodules, which progressively increase in size until a maximun is reached, in about 90 days. At first the nodule is similar to that produced by dust which is absorbed. Later the fibroblasts are replaced by macrophages, which become filled with dust particles. Miller and Sayers give the following examples of this group:

Bisque ware—ground semivitreous pottery bisque ware, fired at a relatively low temperature. Total silica, 72.0 per cent; quartz, about 40 to 50 per cent; the remainder semifused clay and feldspar.

Chert—total silica, 76.1 per cent; quartz about 25 per cent; other forms of free silica, 35 per cent.

Diatomite—total silica, 92.5 per cent; aluminum oxide, 3.5 per cent; ferric oxide, 1.5 per cent; calcium oxide, 0.4 per cent; magnesium oxide, 0.7 per cent; essentially pure diatomite.

Greenware—ground vitreous unfired pottery ware.

Porcelain enamel frit—total combined silica, 35 to 50 per cent; the remainder is oxides of antimony, zinc, and aluminum, and fluorides of sodium, aluminum, and calcium.

Quartz—a pure mineral dust; normal crystalline quartz of high purity (SiO_2).

Quartz—identical with the above sample but treated with 0.6 per cent crude pine fatty acids.

Quartz-sericite—the source of this dust is unknown. Chemical analysis: total silica, 81.04 per cent; calcium oxide, 0.30 per cent; magnesium oxide, 0.45 per cent; sodium oxide, 0.10 per cent; potassium oxide, 0.98 per cent; iron oxide, 0.25 per cent; aluminum oxide, 14.25 per cent; total water, 2.61 per cent. Petrographic examination: quartz, about 50 per cent; muscovite (variety, sericite), about 45 per cent; fibrous sericite, less than 5 per cent.

Bisqueware, chert, greenware—containing from 69 to 76.1 per cent total silica and 25 to 50 per cent of this as quartz.

Diatomite—essentially pure and containing 92.5 per cent total silica.

Quartz—samples of pure mineral dust and industrial dust containing over 99 per cent SiO_2.

Quartz-sericite—about 50 per cent quartz and 50 per cent varieties of sericite.

Tripoli—total silica, 98.9 per cent; chalcedonic silica (crystalline aggregates) with an occasional crystal of normal quartz.

Dust Causing an Inert Reaction. Pneumoconiosis resulting from some of the forms of dust that are inert in the peritoneum has been reported. Clinical and pathological examples of the reactions show modified nodular fibrosis if the dust contains appreciable quantities of free silica; with other types of inert dust, diffuse interstitial fibrosis may sometimes result. The nodules produced in experimental animals become gradually flattened, and the dust is dispersed into the adjacent connective tissue, often to a considerable distance. Inert dust must be considered as a possible potential cause of pulmonary fibrosis. It is much less likely to cause pneumoconiosis than is dust that produces cellular proliferations in the peritoneum. Dust samples of the following descriptions were shown by Miller and Sayers to be inert:

Aluminum—pure aluminum bronzing powder of the finest grade.

Alundum—total silica, 4.6 per cent; aluminum oxide, 88.4 per cent; ferric oxide, 6.9 per cent.

Asbestos—total silica 37.5 to 50.86 per cent.

Anthracite coal—total silica, 6.6 to 8.6 per cent.

Bentonite—clay, variety montmorillonite, about 97 per cent; feldspar, about 2 per cent; quartz, none observed.

Bisque ware—ground vitreous pottery bisque ware, fired at a relatively high temperature. Quartz, about 30 to 40 per cent; the particles were wholly or partially covered by the glass phase. (This is absent in semivitreous bisque ware.)

Bituminous coal—total silica, 0.8 to 3.5 per cent.

Calcium phosphate—petrographic examination: earthy phosphates (not apatite), about 97 per cent; normal and chalcedonic quartz, about 3 per cent.

Chromite—total silica, 7.8 per cent; quartz, less than 5 per cent.

Diamond dust—pure bortz diamond dust used as abrasive.

Feldspar—total silica, 65.9 per cent; calcium oxide, 0.81 per cent; magnesium oxide, 0.10 per cent; aluminum oxide, 19.55 per cent; iron oxide, 0.28 per cent; potassium oxide, 8.98 per cent; sodium oxide, 3.18 per cent. Petrographic examination: feldspar (plagioclase-microcline), about 95 per cent; normal quartz, about 5 per cent.

Fuller's earth—filtral clay, containing from 55.7 to 62.1 per cent total silica and 1 to 10 per cent quartz.

Glass wool—finely ground sample of commercial hard glass wool.

Hematite (jewelers' rouge)—total silica, 1.5 per cent; iron oxide, 98.3 per cent.

Kaolin—china clay and hydromica predominant; quartz and feldspar, a trace.

Lanthanum sublimate—from the burning of white flame electrodes. Lanthanum, 40.0 per cent. Petrographic examination: particles too small to identify.

Mica—silica, 46.92 per cent; magnesium oxide, 0.86 per cent; aluminum oxide, 34.95 per cent; ferric oxide, 2.65 per cent; potassium oxide, 9.54 per cent; sodium oxide, 1.02 per cent; manganese dioxide, trace. Petrographic examination: mica, both as plates and fibers, plates predominating, about 98 per cent; a very small amount of quartz and feldspar.

Precipitator ash—composed of siliceous material, magnesium, iron, aluminum and calcium oxides, or rare earth oxides of the cerium group. The total silica content ranges from 0 to 48.3 per cent and the quartz from 0 to 5 per cent.

Pyrophyllite—predominantly pyrophyllite, with a small amount of rutile and a small undetermined quantity of quartz.

Rock wool—a finely ground sample of commercial, insulating rock wool.

Selenium—selenium, 98.8 per cent; tellurium, 0.01 per cent; ash, 1.16 per cent.

Selenium—a chemically prepared sample of highest purity.

Sericite—a pure mineral dust. Total silica, 51.74 per cent; calcium oxide, 0.61 per cent; magnesium oxide, 1.74 per cent; sodium oxide, 3.40 per cent; potassium oxide, 4.48 per cent; iron oxide, 5.83 per cent; combined oxides, 31.82 per cent; total water, 6.26 per cent. Petrographic examination: sericite and feldspar residues (fibrous sericite predominates), about 95 per cent; quartz, less than 5 per cent.

Shale—silica, 61.0 per cent; aluminum oxide, 12.4 per cent; calcium oxide, 4.5 per cent; ferric oxide, 5.0 per cent; magnesium oxide, 1.3 per cent; sodium oxide, 2.3 per cent; potassium oxide, 1.5 per cent; moisture, 10.3 per cent. Petrographic examination: about 35 per cent quartz; the majority of the particles appeared to be coated with clay.

Silicon carbide—pure manufactured silicon carbide. Silicon, 67.5 per cent. Petrographic examination showed no impurities.

Soapstone—total silica, 36.8 to 49.9 per cent; calcium oxide, 1.7 to 5.0 per cent; magnesium oxide, 22.7 to 26.2 per cent. Petrographic examination: talc, about 55 to 65 per cent; dolomite, about 5 to 30 per cent; tremolite, about 15 to 30 per cent. No quartz observed.

Talc—total silica, 49 to 56.54 per cent; calcium oxide, 6.25 to 8.8 per cent; magnesium oxide, 22.6 to 30.74 per cent; calcium silicate, 0 to 11.00 per cent; calcium carbonate, 0 to 1.88 per cent; iron and aluminum oxides, 0 to 1.04 per cent; ignition loss, up to 4.60 per cent. Petrographic examination: talc, mostly fibrous, about 40 to 75 per cent; tremolite, about 25 to 60 per cent; calcite and (or) dolomite, up to 1 per cent.

Titanium oxide—a finely divided, high-purity sample.

Sodium silicate—a laboratory-prepared sample containing 1 part sodium oxide to 3.1 parts silica. Higher ratios of sodium oxide killed the animals.

Trap rock—silica, 51.7 per cent; aluminum oxide, 16.0 per cent; ferric oxide, 2.0 per cent; ferrous oxide, 9.9 per cent; calcium oxide, 10.0 per cent; magnesium oxide, 6.2 per cent. Petrographic examination: feldspar, some slightly decomposed, about 45 per cent; pyroxene, about 45 per cent; magnetite, about 10 per cent; biotite, about 1 per cent.

Volcanic ash—silica, 54.4 per cent; aluminum oxide, 14.5 per cent; ferric oxide, 3.8 per cent; magnesium oxide, 2.6 per cent; calcium oxide, 0.7 per cent; ash, 78.2 per cent. Petrographic examination: fine volcanic ash partially altered to montmorillonite. No quartz observed.

Volcanic ash—a specially treated sample. Silica, 74.3 per cent; mixed oxides, 16.8 per cent; ferric oxide, 2.2 per cent; calcium oxide, 0.5 per cent; magnesium oxide, 2.2 per cent. Petrographic examination: glass only. No quartz or calcite observed.

The immediate response of body tissue to any dust is essentially a foreign-body reaction, but the subsequent behavior of the tissue to any given dust determines whether such a dust is harmful.

In the peritoneal injection experiments of Miller and Sayers only dust containing free silica caused fibrous proliferations.

Although it has been well established that silicon dioxide is the cause of silicosis, there has been little satisfactory explanation for its action. Earlier it was thought that the fibrous nature of the proliferation was related to the hardness or sharpness of the particles. However, Gardner[27] found that no fibrosis was produced by experimental inhalation of carborundum dust, which was even harder and sharper than silica. Thus, the action is clearly chemical, but the exact chemicophysiological reaction that takes place is still unknown.

The mixed reaction sometimes produced by dusts of the inert group in which silica is mixed with other minerals emphasizes the possible effect of mixed dusts on the development of silicosis. The probable importance of concomitant exposures has also been indicated by clinical experience. Chapman,[28] MacDonald and his associates,[29] and Kilgore[30] have reported cases of rapidly developing silicosis caused by breathing air with high concentrations of silica and alkali dust. Kettle[31] and McCord[32] failed to demonstrate such action experimentally. McCord, on the basis of extensive investigations of workers in six plants where there was exposure to silica and alkali dusts, found no evidence of an accelerator action by alkalies. In fact, the absence of silicosis in this group suggested an inhibitor action which he believes may have resulted from the marked increase in solubility of silica in the presence of alkali. Peritoneal injection in animals yielded no results to prove either an accelerator or inhibitor action of alkali in the formation of silica nodules; but alkali did cause silica to spread from the point of injection and increased its primary toxicity.

The absence of silicosis in ganister-brick manufacturing was thought at first due to an inhibiting effect of accompanying dusts; more recently it has been found

[27] L. U. Gardner, *Am. Rev. Tuberc.*, **20**, 883 (1929).
[28] A. M. Chapman, *J. Am. Med. Assoc.*, **98**, 9 (1939).
[29] G. MacDonald, A. P. Piggot, and F. W. Gilder, *Lancet*, **2**, 836 (1930).
[30] E. S. Kilgore, *J. Am. Med. Assoc.*, **99**, 1414 (1932).
[31] E. H. Kettle, *Proc. Inst. Mining Metallurgy (London) 43rd Sess.*, 1934.
[32] C. P. McCord, *Ind. Med.*, **5**, 17 (1936).

that the concentration of free silica in the work atmosphere was too low to cause fibrosis. Silicosis as found in coal miners (anthracosis) and in foundry men may be quite different in x-ray appearance and in its course from that observed in quartz grinders.

Gardner[33] investigated these effects experimentally using ferruginous chert and mixtures of quartz and calcined gypsum. He found that the percentage of free silica in air-borne dust may not be the same as in the parent substance. This fact may explain the slowness in development of silicosis in workers in certain areas and in certain types of work. When a mixture of calcined gypsum and quartz was present in air, particles of both minerals flocculated and the rate of settling of the mixture was greater than that of either dust in the pure state. Injection experiments with ferruginous chert showed that the iron in the mixture temporarily inhibited the action of silica. Gardner's summaries of these experiments follow:

1. Artificial mixture of equal parts of calcined gypsum and quartz. Materials ground separately to respirable sizes and mixed in a dusting hopper.

Quartz content of parent mixture	49.7%
Quartz content, air-floated dust in cages	29.6%

Average light-field count, air inside cages, 336 million particles per cu. ft.

No exposed animals developed silicosis within 25 months although only 15 months were required to produce nodulation with average concentration of 120 million particles pure quartz per cu. ft. of air. Of 17 animals exposed more than 25 months and up to 30 months, 7 showed nodular fibrosis of modified type. Remaining 10 developed only chronic pneumonitis.

2. Artificial mixture of 2 parts of calcined gypsum and 1 part of quartz prepared as above.

Quartz content of parent mixture	31.4%
Quartz content, air-floated dust in cages	17.1%
Quartz content, lung ash of exposed animals	15.4%

Average light-field count, air inside cages, 245 million particles per cubic foot of air.

No animal developed silicosis until exposures had been continued for 24 months. Mature nodules found in only 3 of 16 guinea pigs exposed 24–29 months. These lesions were of modified type. The other 13 showed nonnodular pneumonitis.

3. Ferruginous Chert I, a natural mixture ground at a mine to such size that a majority of the particles were less than 10 microns in diameter, but there were a considerable number of larger ones.

Free SiO_2 of parent mixture	54.6%
Free SiO_2 of settled rafter dust	38.4%
Free SiO_2 of air-floated dust in cages	10.4%
Free SiO_2 of lung ash of exposed animals	3.3%

Average light-field count, air in cages, 776 million particles per cubic foot.

No suggestion of silicotic reaction but merely pigmentation of lungs of animals exposed for maximal period, 18 months.

4. Ferruginous Chert II. A similar natural mixture from the same source as that used in exp. 3 but ground until all particles were 5 microns and less in diameter.

Free SiO_2 of parent material	67.5%
Free SiO_2 of settled rafter dust	61.0%
Free SiO_2 of air-floated dust in cages	33.5%
Free SiO_2 of lung ash of exposed animals	16.3%

[33] L. U. Gardner, "Reactions to Mixed Dusts," in *Fourth Saranac Laboratory Symposium on Silicosis*, B. E. Kuechle, ed., Employers Mutual Liability Insurance, Wausau, Wis., 1939.

Average light-field count, air in cages, 776 million particles per cubic foot.
No silicosis in any animal's lungs exposed under 3 years; in 8 of 15 animals exposed for longer periods, modified nodules were present. The other 7 developed only pigmentation and chronic pneumonitis.

Thus we have both laboratory and clinical demonstration of the influence exerted by other dust on the development of silicosis.

2. Number of Particles Inhaled in Relation to Production of Fibrosis

From the findings of Gardner, quoted above, and from the discussion of flocculation and settling, in the preliminary section, it is apparent that the type of dust may play an important part in determining the number of particles in the workroom atmosphere. Not only may some components of admixtures flocculate and thus change the character of a dust, but silica itself, being a hard material with a tendency to form large particles as compared with those formed by softer minerals, may settle out more quickly than other components of a mixed dust.

However, at this point we are somewhat more concerned with the concentrations of dust that are harmful than with the factors that have produced any given concentration in the air. Determinations of free and total silica in the lungs of patients who have died after fibrosis developed and in those without fibrosis have been made by incinerating the lungs and chemically analyzing the ash for its silica content. Although there have been some variations in published data on the amount of silica in pulmonary tissue necessary to produce silicosis, Sladden,[34] McNally,[35] Badham and Taylor,[36] and Fowweather[37] found fairly comparable amounts. Drinker and Hatch[38] sum up the present knowledge somewhat as follows: as a rough guide, a total silica content as high as 0.2 per cent of dried lung can be considered normal. A content over 1 per cent is definite evidence of dust exposure, and this amount is usually accompanied by fibrosis. There is too much overlapping of data and variation in technique to be sure from published data of the significance of quantities between 0.2 and 1 per cent of ashed lung. This fact is of especial significance, as pointed out by Cummings.[39] Since there is usually no evidence of silicotic reaction in lungs containing less than 1.5 to 2 gms. of silica (1 per cent of weight of dried lung), it may be inferred that the contraction of silicosis does not necessarily follow the inhalation of silica. Silicosis occurs only after the inhalation of amounts in excess of a minimum.

In any control program we are of course concerned primarily with the amount

[34] A. F. Sladden, *Lancet*, **2**, 123 (1933).
[35] W. D. McNally, *J. Am. Med. Assoc.*, **101**, 584 (1933).
[36] C. Badham and H. B. Taylor, *Med. J. Australia*, **1**, 511 (1933).
[37] F. S. Fowweather, *Chem. Industries*, **53**, 713 (1934).
[38] P. Drinker and T. Hatch, *Industrial Dust—Hygienic Significance, Measurement and Control*. McGraw-Hill, New York, 1936.
[39] D. E. Cummings, "The Etiology of Silicosis," in *Fourth Saranac Laboratory Symposium on Silicosis*, B. E. Kuechle, ed., Employers Mutual Liability Insurance, Wausau, Wis., 1939.

of dust in the air that will cause fibrosis. The methods of determining atmospheric dust concentrations are discussed in Chapter Eight. Cummings suggested that atmospheric concentrations of silica dust should be considered in terms of two thresholds: the primary threshold, a level at which a healthy man can be employed for his lifetime without harm, about 5,000,000 particles per cubic foot (light-field count); and the secondary threshold, a level at which a healthy man will inevitably develop silicosis, about 100,000,000 particles per cubic foot (light-field count). The National Silicosis Conference summarizes the situation as follows: "There is evidence that for prolonged exposure a concentration of more than 5 million particles per cubic foot, of a highly siliceous dust, is dangerous. Therefore it is now considered good practice to hold concentrations of highly siliceous dust at 5 million particles per cubic foot, or less," as based on light-field counting methods.

Since standards of safe atmospheric dust concentration based on medical findings have been suggested tentatively for only a few industrial dusts, and since considerable study is necessary to form a basis for such standards for other industrial dusts, a tentative arbitrary measure of what is good practice may be used. This should be within the limits of good engineering practice and yet low enough to control the silicosis hazard for most industrial exposures. The following formula is frequently used to express the maximum permissible concentration of silica in air:

> Multiply the percentage of free silica by the total dust particle count per cubic foot (light-field technique). If the result is over 5 million, the concentration may be considered too high. For example: a dust containing 10 per cent free silica with an average total concentration of 30 million particles per cubic foot would give 0.10 times 30 million, which equals 3 million (good practice); a dust containing 30 per cent with an average total concentration of 50 million particles per cubic foot would equal 0.3 times 50, or 15 million (unsatisfactory). This formula is not applicable to any dust containing less than 5 per cent free silica.

The Division of Industrial Hygiene, National Institute of Health,[40] has suggested that an attempt should be made to have highly siliceous dusts kept at a concentration below 4,000,000 particles per cubic foot since considerable silicosis occurred in the pottery industry even with low dust concentrations.

Dust may also be simply a nuisance. It is considered good practice to control even relatively harmless dust sufficiently to prevent concentrations in excess of 50,000,000 particles per cubic foot (by light-field count) in the workroom air.

3. Particle Size in Relation to Development of Fibrosis

We have already mentioned the fact that large particles settle more rapidly than small ones and that particle size is important as a determining factor in the actual amount of dust in air. Particle size is even more important in determining the chemical activity of the dust and physiological responses to it. Chemical activity is, of course, increased in small particles because of the increased surface area. McCrae[41]

[40] R. H. Flinn, W. C. Dreessen, T. I. Edwards, E. C. Riley, J. J. Bloomfield, and R. R. Sayers, *U.S. Pub. Health Bull.* No. **244** (1939).

[41] J. McCrae, *Pub. S. African Inst. Med. Research*, Report No. 3 (1913).

found that 70 per cent of the particles in silicotic lungs were less than 1 μ in diameter and that the largest were not greater than 10.5 μ. An upper limit of 10 μ as the maximum size that will produce silicosis has been suggested because larger particles are probably collected by mucus in the upper respiratory tract and moved out of the lungs by ciliary action. The importance of small particles in the production of fibrosis has been well demonstrated by Tebbens, Schulz, and Drinker.[42] These investigators produced liver fibrosis in experimental animals by intravenous injections of suspended silica and found that particles less than 0.6 μ in diameter caused much more fibrosis than larger particles.

Briefly, silicosis is caused by the inhalation of silica particles less than 10 μ in diameter. Recent work suggests that particles of less than 0.6 μ may be of greatest importance in this respect.

4. Individual Predisposition

Detailed discussion of the role of individual predisposition in the etiology of silicosis is hardly necessary. Race and sex seem to play little part, although race may be a factor in the development of tuberculosis just as financial status may be a factor. Certainly it is known that of two persons working in the same dusty exposure one may contract silicosis in a few years while the other may wholly escape it. We have already mentioned the possible influence of differences in nasal filtration as a factor in causation of silicosis. It is likely that there are sound explanations for the many variations in individual susceptibility, but clarification is lacking.

D. PATHOLOGICAL ANATOMY AND X-RAY FINDINGS

Gardner,[43] whose descriptions of pathological anatomy have been used as a basis for much of this discussion, has classified the pneumoconioses as follows: *Nonspecific pneumoconiosis*, including all forms except silicosis and asbestosis, *silicosis* of the classical discrete nodular type, *modified silicosis* caused by the inhalation of dusts containing free silica mixed with certain other minerals, and *silicosis with conglomerate lesions*, in which healed or active infection probably plays a dominant role.

1. Nonspecific Pneumoconiosis

All dust other than that containing free silica and asbestos produces the same general reaction.

X-ray Examination. There is simply an accentuation of the normal, branching, treelike shadows cast chiefly by the pulmonary blood vessels. As an occasional variation in this picture there may be superimposed fine reticulations. These reticulations are thought to be caused by thickening of the sheaths of the pulmonary arteries and thickening of the interlobular septa. See Figures 4 and 5.

[42] B. D. Tebbens, R. Z. Schulz, and P. Drinker, *J. Ind. Hyg. Toxicol.*, **27**, 199 (1945).

[43] L. U. Gardner, in *Fourth Saranac Laboratory Symposium on Silicosis*, B. E. Kuechle, ed., Employers Mutual Liability Insurance, Wausau, Wis., 1939.

Gross Examination. Except with prolonged and intensive exposure, the pleural surfaces of lungs with nonspecific pneumoconiosis show only focal and linear collections of pigment that are soft in consistency and not raised above the surrounding tissues. On cut surfaces, gross examination reveals rounded flecks of pigment 2 to 3 mm. in diameter, but a lens shows finer linear deposits in the interlobular septa and in the outer walls of the blood vessels. The entire lung may be colored by pigment as in the black lung of soft-coal miners, but no fibrosis is found unless there has been exposure to free silica. There may be small patches of emphysema in or adjacent to pigmented areas. Scars of healed infections differ from the usual scars by the presence of pigment.

Microscopic Examination. If death occurs during exposure, dust particles are found free in the peripheral air spaces or ingested by alveolar phagocytes that are found adherent to alveolar walls and in loose areolar tissue about the blood vessels, especially the arteries, and in the interlobular septa. These last two linear deposits are referred to as perilymphatic deposits because of their close relationship to the lymphatic trunks. The bronchi show relatively little dust; when any is present, however, it is found in the connective tissues just beneath the epithelium. If there has been no recent exposure (years), the intrapulmonary dust tends to be removed from the air spaces and deposited along the lymph trunks; in severe exposure large amounts of dust-filled phagocytes may remain in the alveoli. Nearly all pure substances other than silica cause little cellular reaction. Coal and some silicates, especially mica, may cause minor irritation without producing fibrosis. Unless the linear reaction is fibrous and caused by free silica, there is no altered susceptibility to tuberculosos.

2. Discrete Nodular Silicosis

X-Ray Examination. This form of dust disease is characterized in the x-ray by small discrete nodular shadows, uniformly distributed throughout all parts of both lungs with the possible exception of small emphysematous areas in the costophrenic region. In the absence of infection, the nodules are of uniform size, rarely exceeding 4 mm. and never more than 6 mm. in diameter. The nodules are sharp with well-defined borders. See Figures 6 and 7.

Gross Examination. The pleurae are studded with slightly elevated, grayish nodules 2 to 3 mm. in diameter, and around these there may be a flat zone of black, gray, or brown pigment. No pleural adhesions are present. The lungs are stiffer than normal but crepitus is present. There are palpable shotty nodules. The cut surfaces are seeded with black or gray nodules, 2 to 4 mm., or rarely 6 mm., in diameter. The edges of the nodules are well defined, but a lens shows pigmented strands radiating from their periphery. There is little confluence except where scars or infection are present. Usually some gross emphysema is present, but this condition may be apparent only with microscopic examination. For differentiation from perilymphatic pigmentation there must be definite pleural nodulation in an appreciable amount. Some nodules may arise along the peripheral branches of the pulmonary arteries.

Fig. 4. Normal chest.

FIG. 5. Increased linear markings. Increased linear markings may be seen in the roentgenograms of apparently healthy subjects, and they may result from infection, exposure to irritants or dust or from other causes. Increased linear markings may also be demonstrated in patients who later develop nodular silicosis. A definite diagnosis of pneumoconiosis can not be made from roentgenograms showing only increased linear or vascular markings.

FIG. 6. Nodular silicosis, uncomplicated (*courtesy L. E. Hamlin*).

FIG. 7. Nodular silicosis with infection in right upper lobe (*courtesy L. E. Hamlin*).

FIG. 8. Increased linear markings and indistinct nodulation. This type of abnormality is sometimes seen in roentgenograms of subjects exposed to mixed dust. This roentgenogram is about midway between that seen in nonspecific pneumoconiosis and that seen in nodular silicosis.

FIG. 9. Nodular silicosis with conglomerate lesions. It has been pointed out in the text that conglomerate lesions are ordinarily associated with infection, usually tuberculous. It is of interest to note that this patient was negative to tuberculin (P.P.D. first strength) and that he had had eleven sputums that were negative and none positive for tubercle bacilli (*courtesy L. E. Hamlin*).

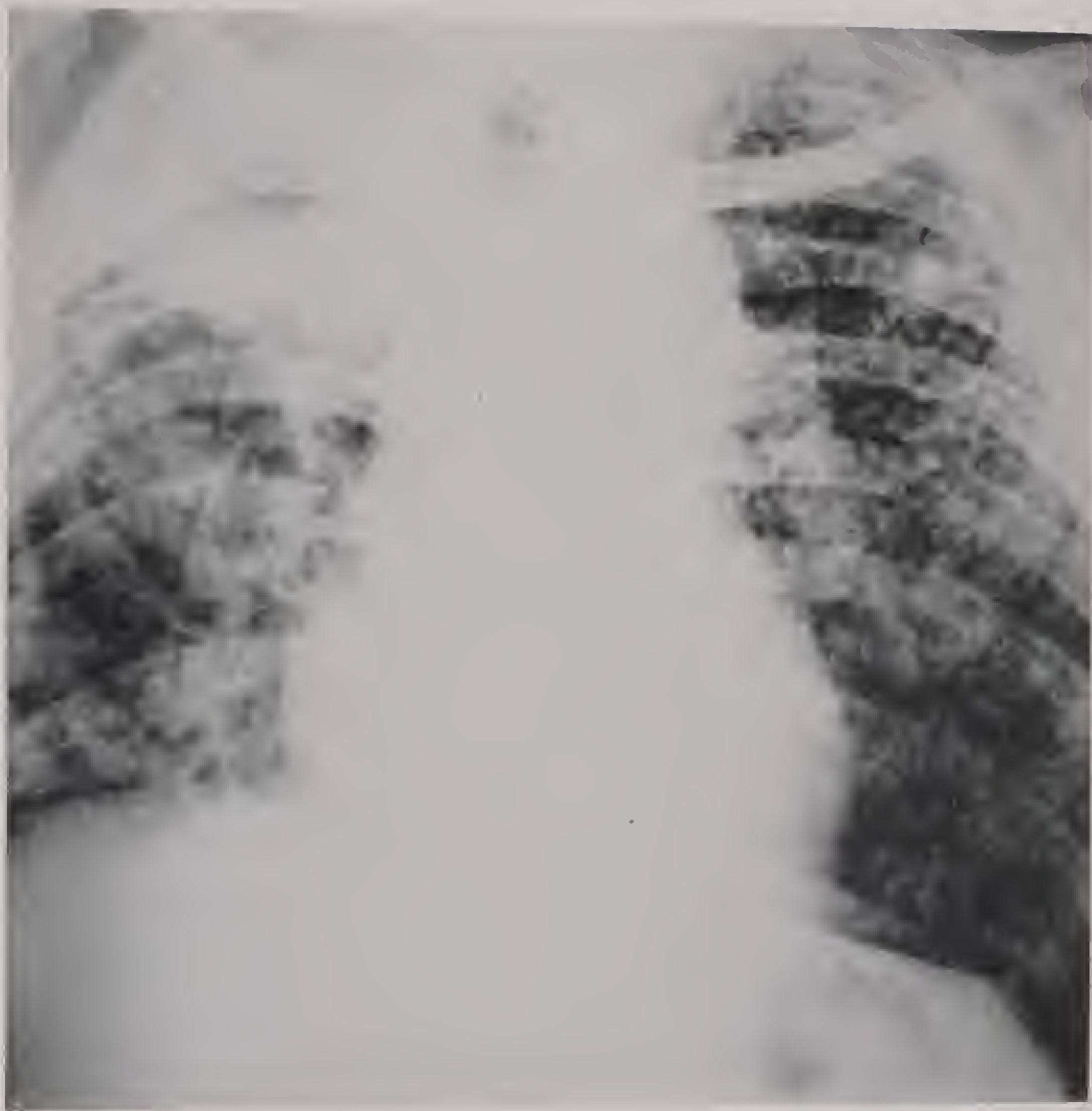

Fig. 10. Nodular silicosis with conglomerate lesions and infection
(*courtesy L. E. Hamlin*).

The tracheobronchial lymph nodes are at first enlarged and firm, later small and extremely hard. Sections of these nodes reveal dense leatherlike tissue, which is silky in texture because of the decrease in collagenous connective tissue.

Microscopic Examination. Microscopic examination shows layers of dense hyaline collagenous fibers with nuclei so compressed as to be almost invisible at times. The borders are clear cut, with no exudation. There may be pigment either about the periphery or in focal points within the nodule itself. The nodule may be calcified, occasionally to the point of bone formation in its central portion. Nearly all nodules are associated with branches of the pulmonary arteries, as demonstrated by wax reconstruction of the arteries; they may form spherical or spindle-shaped masses around the arteries. Pigmentation occurs about the lymphatic trunk just as in nonspecific pneumoconiosis, but there is always some fibrosis. The air spaces immediately adjacent to the nodules are distorted and frequently dilated. There may be widespread emphysema, most marked in the costophrenic angle, where nodulation is most sparse. The emphysema is fine, not coarse or bullate. Ordinarily there is no leukocytic reaction. Early silicosis resembles nonspecific pneumoconiosis; the reaction, however, is more extensive and is fibrous rather than cellular. The closely related pathological pictures in early silicosis and in the nonspecific reaction would be expected since the x-ray findings in the two conditions are almost identical. Neither in early silicosis nor in nonspecific pneumoconiosis are the x-ray findings associated with any disability.

3. Modified Silicosis

Modified nodulation results from breathing dust containing free silica mixed with other minerals. Although a great deal is not known about mixed dust reactions, there have been sufficient examinations of the lungs of hard-coal miners to determine that lung tissue responds differently to the dust of coal mines than to pure silica dust.

X-Ray Examination. Long experience in interpretation of roentgenograms of silicotics with varied exposures may enable one to conjecture with a reasonable degree of accuracy the general type of exposure. Large amounts of nonsiliceous or silicate dust in the mixture tend to induce perilymphatic deposits of the linear type. Free silica intensifies this reaction and causes it to become fibrous. At times hyaline nodulation occurs, perhaps when there is enough free silica in the dust, but this reaction is atypical. Gross examination of the modified silicotic nodules may reveal heavy deposition of pigment with or without dense fibrosis. With a hand lens hard elevated nodules may be seen in the centers of some of the pigment deposits. See Figure 8.

Microscopic Examination. On microscopic examination it will be seen that many of the nodules consist of nothing but coarse, heavily pigmented fibers devoid of organized arrangement. Such nodules may have irregular peripheral extensions, which fuse with those of others. (This fusion of nodules may be partly responsible for the appearance produced in the conglomerate reaction.)

4. Nodular Silicosis with Localized Conglomerate Lesions

X-Ray Examination. X-ray examination shows isolated or bilaterally symmetrical massive shadows usually located in the upper half of the lungs but sometimes in the lower third. These massive shadows may extend from the root to the pleural surface, or they may lie deep in the parenchyma. Serial x-rays may show that the lesions remain stationary over a period of five to six years or they may show an increase in size on successive pictures. Ultimately central rarefaction, interpreted as cavitation, may develop with subsequent evidence of infection in other parts of the lung (see Figures 9 and 10). Gardner[44] presents the following working hypotheses with regard to conglomerate lesions:

"1. In tuberculo-silicosis the infection may heal so completely that its tuberculous origin is no longer recognizable. Such an outcome has been observed in experimental animals exposed to ferruginous chert and infected with attenuated tubercle bacilli.

"2. Conglomerate lesions in the upper lung fields, particularly when they are bilateral, are in the great majority of cases due to an underlying tuberculosis in healed or latent form. In persons not exposed to dust, bilateral disease in this location proves to be tuberculous in 95 to 98 cases out of every hundred, and even unilateral disease can safely be considered tuberculous in 90 per cent of cases.

"3. Large isolated or bilaterally symmetrical conglomerations in the lower lungs should be considered tuberculous unless this origin can be excluded. In that case the possibility of organizing pneumonia due to Friedlander's bacillus or other organisms should receive consideration.

"4. The character of the fibrosis resulting from the combined activity of an infectious organism and silica dust with or without other minerals may suggest a relationship between the time of exposure to dust and the development of the infection.

"(a) When the silicosis is already established before tuberculosis supervenes the infection localizes in and about the nodules which retain their form but increase in size. Bronchial obstruction *caused by the infection* may produce widespread atelectasis with a consequent approximation of the nodules in the involved area. In such cases the outlines of large, individual nodules in the resultant conglomeration are distinct and clearly defined.

"(b) When silicosis and chronic tuberculosis have developed simultaneously the nodular character of the conglomerate fibrosis is less obvious. Nodules are present but they are surrounded by a matrix of more diffuse fibrosis produced by the action of the silica upon an organizing pneumonic process.

"(c) When the scars of a healed infection are already present before employment in the dusty industry, the inhaled particles accumulate in particularly large quantities in their immediate vicinity. Continued accumulation in the localized area produces many nodules, which are small because they are closely packed together but typically spherical in outline because there is no activity in the underlying infections process to produce diffuse fibrotic reaction."

Many patients with conglomerate silicotic fibrosis are dyspneic, but the toxic symptoms of the associated infection may be absent. This is reasonable, since healed tuberculosis does not cause symptoms and even active infections may be so well encapsulated by dense fibrous tissue that no tissue reaction is possible.

E. TUBERCULOSILICOSIS

The relationship between silica exposure and the development of tuberculosis has been well demonstrated in the United States as well as in other countries where

[44] L. U. Gardner, "Pathological Anatomy" in *Fourth Saranac Laboratory Symposium on Silicosis*, B. E. Kuechle, ed., Employers Mutual Liability Insurance, Wausau, Wis., 1939.

there has been such exposure. One of the most remarkable demonstrations of the relation of tuberculosis to silica dust exposure is found in the work of Mavrogordato,[45] illustrated graphically in Figure 11.

The symptomatology and clinical findings in silicosis and in silicosis complicated by tuberculosis have been summarized in the National Silicosis Conference Report of the Committee on Medical Control, and these have been condensed by Lanza[46] as follows:

"SUBJECTIVE SYMPTOMS: *Dyspnea*—The complaint most frequently mentioned is shortness of breath. Depending upon the extent of the involvement, this varies from slight dyspnea, following exertion, to marked dyspnea upon the least exertion or even when at rest. The shortness of breath noted in silicotics presents one peculiarity in that it is seldom accompanied by orthopnea, the individual being no more short of breath lying down than when in an upright position. This may not be so, however, when silicosis is complicated by cardiac disease or by true asthma.

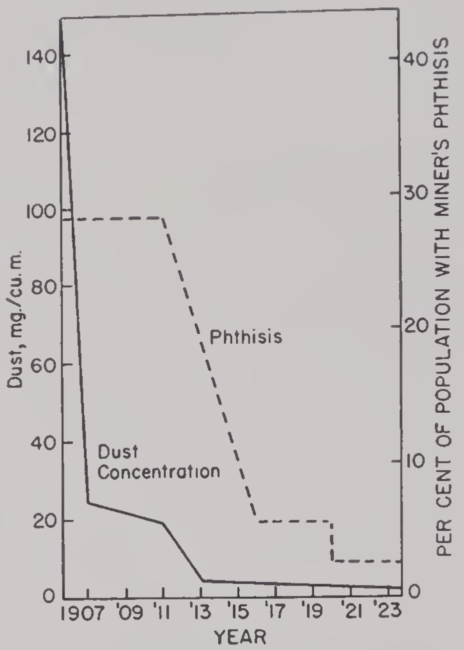

FIG. 11. Dust control and silicosis in South Africa.

Silicosis	Silicosis with infection
Noted as a rule only after sudden or extra exertion. Seldom so marked as to interfere with routine duties. However, in cases with extensive pulmonary fibrosis, it may limit the individual's activities.	If complicating infection is not widespread, may be no more marked than in cases of simple silicosis but as infection and fibrosis increase, it becomes disabling.

"*Cough.* Many silicotics complain of a troublesome cough. This cough differs from that resulting from simple irritation due to dust which clears up upon removal from exposure. When present, it is more pronounced in the morning or upon beginning work after a rest period.

Silicosis	Silicosis with infection
The typical silicotic cough is dry and nonproductive. It usually parallels shortness of breath in degree and may contribute to disability.	The cough usually becomes more troublesome and is productive. The sputum varies from thick, tenacious, mucous material to that of a foul, purulent or purohemorrhagic consistency. Microscopic examination or animal inoculation frequently reveal tubercle bacilli or, in some cases, organisms of the fusiform spirochetal group. In advanced cases, coughing attacks are often of such severity as to leave the individual exhausted.

"*Chest Pain.* This symptom is complained of by a majority of silicotics. It varies from a feeling of tightness in the chest to the sharp pain typical of pleurisy. (Since chest pain is offered as a complaint in many conditions, it cannot be stressed as especially characteristic of silicosis.)

[45] A. Mavrogordato, *Pub. S. African Inst. Med. Research*, Report No. 19 (1926).
[46] A. J. Lanza, *Silicosis and Asbestosis*. Oxford Univ. Press, New York, 1938.

Silicosis

A late symptom in cases of simple silicosis. Then seldom more than a sense of tightness or feeling of substernal pressure.

Silicosis with infection

Pleuritic pain is suggestive of a complicating infection. It is increased by exercise and by coughing and may be distressing in advanced cases with extensive infection.

"*Hemoptysis.* True hemoptysis seldom occurs. Frequently, however, the sputum may be blood-streaked following a severe coughing attack. Hemoptysis must always be considered as suggestive of tuberculosis.

Silicosis

Occaional blood-streaked sputum. May result from alveolar rupture following sudden exertion in advanced cases.

Silicosis with infection

May be the first indication of tuberculous infection. May be consequent upon the development of pneumothorax. May occasionally be excessive if cavities are present.

"*General Complaints.* Weakness, loss of weight, digestive disturbances, night sweats, insomnia, dizziness, and edema of the extremities are not characteristic of uncomplicated silicosis but are apt to be present if infection supervenes, especially when the infection becomes extensive.

"*OBJECTIVE SYMPTOMS*: Changes in the general appearance are infrequent in simple silicosis unless far advanced. Such changes as are manifested are usually due to complicating conditions.

Silicosis

Early cases appear unchanged; in fact, it is common to find these individuals showing a slight increase in weight, possibly because they are less active. As the disease progresses, respiratory embarrassment is noticeable and there is a general loss of muscle tone.

Silicosis with infection

The appearance sooner or later becomes that of chronic phthisis. The bony landmarks of the thorax become prominent and there is an increase in the anterior-posterior diameter of the chest, possible hypertrophy of the accessory respiratory muscles of the chest, and in the final stages, retraction of the supra and infra clavicular spaces. Cyanosis and clubbing of the fingers are not prominent except in those cases of long standing, with cardiac disturbances.

"*Chest Expansion.* Decrease in the expansion of the chest may be demonstrated in cases with extensive pulmonary fibrosis.

Silicosis

In early cases it is usually not possible to demonstrate decreased expansion. In advanced cases, expansion may be lessened by 20 to 30 per cent but remains equal on both sides.

Silicosis with infection

Decrease in expansion may not be noted in early silicosis with slight infection but as the condition progresses, a definite decrease is readily observed. When infection is more pronounced in one area of the lung, expansion may be more markedly decreased on the affected side, particularly if there is pleural involvement.

"*Prolonged Expiration.* In most cases, decreased chest expansion is preceded and later accompanied by a definite change in respiratory rhythm. Close observation reveals that even at rest there is a distinct tendency to prolongation of the expiratory phase, which, as silicosis advances, becomes more marked. Following exercise, the silicotic may breathe less rapidly than the normal person under similar conditions as the lungs cannot be emptied rapidly enough to permit more rapid respiration; but although the respiratory rate is not so rapid as in the normal person, it will persist for a longer period.

Silicosis

Early in the development of a simple silicosis, prolonged expiration may be evident only after exertion. Later the degree of prolongation usually parallels the increase in pulmonary fibrosis.

Silicosis with infection

In cases of early silicosis with slight infection, prolongation of the expiratory phase may be no more marked than in simple silicosis. As the condition progresses and fibrosis increases, it may simulate characteristic asthmatic respiratory rhythm.

"*Signs Revealed by Palpation of the Chest.* Except in the late stages of silicosis with infection, little is revealed by palpation of the chest. However, where there is a measurable decrease in expansion, one may note by palpation that, upon forced inspiration, the anterior chest wall is lifted forward by the accessory muscles of respiration.

Silicosis	Silicosis with infection
No change noted until extensive fibrosis has taken place, when there may be an increase in tactile fremitus generally.	When infection is extensive, tactile fremitus is increased and occasionally friction rubs may be elicited. Extensive thickening of the pleura or pneumothorax may result in a decrease or absence of tactile fremitus over affected areas.

"*Percussion.* There is usually an impairment of the percussion noted over the whole chest but unless one is particularly observant, this may not be detected.

Silicosis	Silicosis with infection
Since impairment in resonance is general over all lung areas, it is difficult to demonstrate until advanced fibrotic changes have developed. Decrease in diaphragmatic excursion may sometimes be revealed by percussion.	Increase in loss of normal resonance. When massive areas of fibrosis have developed, this may amount to absolute dullness over areas involved. Amphoric resonance may be elicted where there is pneumothorax. Decreased diaphragmatic excursion may readily be shown in advanced infection.

"*Auscultation.* Breath sounds are usually decreased in intensity and the characteristic prolongation of expiration is readily noted.

Silicosis	Silicosis with infection
Decrease in breath sounds general and more marked as the condition progresses. Subcrepitant râles, which clear up after coughing, are occasionally heard.	Usually heard, some of the following: Persistent post-tussic crepitant and subcrepitant râles; coarse rhonchi associated with productive coughing, wheezing or musical râles increased by exertion and coughing, amphoric breath sounds over cavities and areas of pneumothorax; pleural friction rubs occasionally."

Part of the symptomatology associated with silicosis may be due to pathological processes other than fibrosis. Filley, Hawley, and Wright,[47] using isolated perfused lungs of guinea pigs found that colloidal silica produced bronchial constriction, although soluble silica did not. This at least suggests that part of the disability in silicosis may result from bronchial constriction. Such findings also offer the first rational approach to a basis for explaining the improvement of symptoms in patients with silicosis after aluminum therapy. The inability of soluble silica to cause bronchial constriction, however, raises a question as to the validity of the assumption that this same reaction occurs in workers exposed to silica.

That exposure to silica dust may increase the tendency to contract respiratory diseases other than tuberculosis has been suggested by Sayers.[48] He concludes from a survey of the mining industry that:

"1. The principal pulmonary diseases to which the miner is subject are bronchitis, influenza and pneumonia, pulmonary tuberculosis, anthracosilicosis, and silicosis.

"2. Statistics indicate that much higher morbidity and death rates from pulmonary diseases are experienced in dusty than in nondusty industries, especially where silica dust is used or produced.

"3. Investigations by the Public Health Service reveal that hard-coal miners suffer a high

[47] G. F. Filley, J. G. Hawley, and G. W. Wright, *J. Ind. Hyg. Toxicol.*, **27**, 37 (1945).
[48] R. R. Sayers, *U.S. Bur. Mines Circ.* No. **7146** (1941).

mortality rate from influenza and pneumonia not only during influenza epidemics but at other times as well. In 1915–23 and 1906–25 influenza and pneumonia were responsible for 40 per cent of the total deaths among hard-coal miners, compared with 25 per cent among males at ages 15 to 65 who were engaged in pursuits other than coal mining. Six per cent of hard-coal miners had pulmonary tuberculosis, compared with 2 per cent in the adult male population of the United States. The rate for metal miners is still higher."

F. DIAGNOSIS OF SILICOSIS

To make a definite diagnosis of silicosis one must have (*a*) a roentgenogram with the appearance characteristic of fibrous nodulation and (*b*) proof of the subject's exposure to significant amounts of dust containing free silica. Gardner[49] points out the importance of an occupational history since a nodular or mottled x-ray pattern may occur in other conditions, including so-called "arcwelder's siderosis" and baritosis, in which no fibrous nodulation can be demonstrated by pathological examination. Organic iron from the blood may cast shadows that simulate silicosis. A striking example of the effect of blood is seen in roentgenograms of men trapped underground in mine explosions; serial films demonstrate the sudden appearance of fine nodulations, which disappear in a few weeks. Pulmonary sarcoidosis, a tuberclelike infection of unknown cause, occurring throughout the population at large, may produce similar shadows. Another condition to be considered is miliary calcification of the lungs, commonly called "wheatena"; the dense, not uniformly scattered nodules are thought to represent a stage in the healing of some infection of unknown nature. Likewise, cardiac decomposition may, by the accompanying pulmonary congestion, produce an x-ray picture that somewhat resembles silicosis.

All of this suggests the difficulty in diagnosing silicosis unless full details of all findings are available to the examining physician.

G. EVALUATION OF DISABILITY IN SILICOSIS

1. Statement of the Problem

To both management and labor the term "silicosis" has become nearly synonymous with the term "total disability." Accordingly, some time should be devoted to the details involved in evaluating pulmonary "ability" or "disability" in this disease. Actually, uncomplicated silicosis is almost notorious for its lack of symptoms even in relatively advanced stages. In fairness to both employer and employee it is necessary to go beyond simple diagnosis. In examining a patient with silicosis an attempt should be made to answer certain questions: Does his chest x-ray suggest that he has silicosis? Does he have a history of sufficient exposures to free silica dust to account for any roentgenographic changes present? Does he have complicating tuberculosis or other infection? Is he incapacitated or disabled by the condition? The first three of these questions are usually answered by the examining physician. Too frequently, however, not enough attention is paid to the fourth question, concerning disability. As a result of this an employee may be dismissed from work

[49] L. U. Gardner, *Am. Ind. Hyg. Foundation*, Annual Meeting, Pittsburgh, November 14, 1945.

unjustly or he may collect compensation for disability unjustly. For medical-legal purposes as well as for the purpose of fitting each afflicted employee into work within his capacity it is helpful to have records of progress on individual patients over a prolonged period, preferably many years. Industrial medicine may make some contribution to an understanding of pulmonary physiology by accumulating specific data on large groups of people, and in the final analysis this can best be done by men closely associated with employees, with management, and with the problems of industrial medicine.

We have already summarized the diagnostic criteria for silicosis and have discussed the findings indicative of complicating tuberculosis. It is necessary to bear in mind the fact that cardiac insufficiency, anemia, and other diseases may produce symptoms not readily differentiated from those of pneumoconioses. In establishing a diagnosis of decreased functional capacity from a pneumoconiosis, these diseases must first be ruled out. Dyspnea as a symptom of disease has long been recognized by all physicians, and diagnostic aids such as ordinary laboratory procedures, electrocardiographic studies, and other tests are available for diagnosis of complicating diseases with pneumoconiosis. After a definite diagnosis of silicosis has been established, physiological measurements of pulmonary function may be used as an aid to the usual clinical examination in determining the extent of disability.

2. Pathological Physiology and General Principles

A great deal of work on the physiology of respiration has been done in this country and in Europe. Contributions of especial significance have been made by Cournand and his associates and by McCann and the group working with him. These sources have been drawn upon heavily for the material in this section. Cournand and Richards[50] have suggested a simple, yet useful, classification of the types of pulmonary insufficiency and discussed the mechanisms involved in each type. Their grouping is as follows: (*1*) ventilatory pulmonary insufficiency, which is concerned with defective air movement into and out of the lungs; (*2*) respiratory pulmonary insufficiency, which is concerned with defective gaseous exchange between the blood and alveolar air; (*3*) combined ventilorespiratory insufficiency; (*4*) combined cardiopulmonary insufficiency.

Ventilatory Insufficiency. The ventilatory aspect of pulmonary function is largely mechanical. Adequate ventilation is dependent upon the movement of sufficient air into and out of the lungs, that is, upon a breathing capacity great enough to supply the body with the oxygen necessary for its needs. The flow of air to and from the lung is dependent on the chest bellows, regulated by a well-coordinated neuromuscular mechanism, the tracheobronchial pulmonary air passageway, and the state of pulmonary tissue, particularly as related to the amount of elasticity and fibrosis.

The breathing requirement, or the amount of oxygen required at any given

[50] A. Cournand and W. Richards, Jr., *Am. Rev. Tuberc.*, **44**, 26 (1941).

time, varies with the metabolism, posture, oxygen and carbon dioxide saturation of the blood, emotional or nervous states, and exercise. It is primarily governed by reflex stimulation of the respiratory centers.

The cardinal sign in ventilatory insufficiency is hypercapnia and its concomitant symptom, dyspnea.

Respiratory Insufficiency. The respiratory function is concerned with gaseous interchange between the alveolar air and the blood. This is dependent upon the degree of ventilation of the individual alveoli and the relative number of alveoli that are well ventilated, the number, size, and distribution of capillaries in contact with the alveoli, and the rate of blood flow through these capillaries, as well as the oxygen-carrying capacity of the blood, the gradient of pressure of respiratory gases across the alveolar-capillary partition and the physical properties of this partition.

The cardinal sign in respiratory insufficiency is cyanosis. However, if the insufficiency is slight, cyanosis may not be present and hypercapnia may predominate. In such instances measurements of oxygen removed from inspired air or carbon dioxide added to expired air or of the oxygen saturation of arterial blood may be necessary to determine the actual extent of the respiratory failure.

Cardiocirculatory Insufficiency. The cardiocirculatory function may be affected along with the respiratory and ventilatory functions. The causes of disturbance in the heart and circulation that may be encountered in connection with chronic pulmonary disease are: hypertension in the pulmonary circulation and subsequent right-heart hypertrophy; obstruction to the flow of blood by displacement of the mediastinum, increased pressure in the thorax, or disturbance in the mechanics of breathing; decreased cardiac function due to the effects of anoxia on the heart muscle and cardiac regulatory centers; and independent heart disease of any type.

It must always be borne in mind that patients with heart disease respond to pulmonary function tests similarly to those with pulmonary fibrosis and emphysema.[51] The fact, demonstrated by Enzer, Simonson, and Evans,[52] that recovery of pulse rate during and after exercise is of little value in the segregation of normal persons from those with silicosis may be significant in differential diagnosis of purely pulmonary disease as compared with cardiac disease. However, Enzer himself points out that his tests were performed by subjects who worked until fatigue developed. Enzer's normal subjects actually did more work than his silicotic patients before fatigue occurred, which may account for the lack of difference in the pulse rates. He found, nevertheless, a definite trend toward prolonged recovery time in his patients when certain types of work were done. At any rate there was a greater correlation between lung disease and pulmonary functions than between lung disease and pulse rates after exercise. We believe that information based on some standard form of exercise such as the Master Two-Step Test,[53] which has been

[51] N. L. Kaltreider and Wm. S. McCann, *J. Clin. Investigation,* **16**, 23 (1937).
[52] N. Enzer, E. Simonson, and A. M. Evans, *J. Ind. Hyg. Toxicol.,* **23**, 147 (1945).
[53] A. M. Master and E. T. Oppenheimer, *Am. J. Med. Sci.,* **177**, 223 (1929).

carefully standardized for age and sex, would be helpful in making such an analysis.

A fundamental concept necessary to an understanding of symptoms in any disease is that symptoms develop only when the adaptive mechanism of the body is required to function in a degree beyond that normally required for adaptation. In other words, symptoms appear when the adaptive mechanism is put under strain. This is particularly true in pulmonary disease. As an example, Harrison[54] found that "a person becomes short of breath when his actual volume of breathing becomes more than a certain fraction of his maximum possible volume and the closer the actual volume approaches the maximum possible ventilation, the more severe the dyspnea becomes." Accordingly, measurements that indicate the relative degree of ventilation or aeration required under given circumstances in comparison with the total ability to ventilate or with other known lung capacities are of more value than measurements that indicate merely a particular capacity.

Likewise, as pointed out by Hurtado and Boller,[55] there may be wide normal variations from the median when any one function such as vital capacity or residual air is measured, whereas if this function is taken as a percentage of total capacity the normal variations are much closer to the median. Thus again is demonstrated the value of expressing a capacity in terms of percentage of another capacity.

3. *Terminology*

A serious drawback to the proper comparison of different series of observations on respiratory functions has been the use of different terms and even of different meanings for the same term. It is therefore essential to adopt, if possible, a single nomenclature in order to have a clear understanding of the subject. Christie and Meakins[56] have proposed a fairly satisfactory usage, which we shall adopt here, except for the suggestion of Hurtado and Boller that the term "functional residual air" be replaced by the term "mid-capacity," and with the addition from later authors of terms describing ventilation and its components. The classification as suggested may be summarized as follows:

1. *Residual air* is the amount of air remaining in the lungs after fullest possible expiration.

2. *Reserve air* is the amount of air expired from the mid-capacity position to the maximum possible deflation.

3. *Mid-capacity* is the amount of air remaining in the lungs after a normal expiration. Christie and Meakins speak of this as the resting respiratory level. Hurtado and Boller comment on this as follows: "The term 'functional residual air' is synonymous with this term. It appears to be more convenient, however, to use the term mid-capacity as being more descriptive and more commonly used. The term 'functional residual air' may be easily confused with residual air, or it may suggest that it is a subdivision of the latter. Mid-capacity represents the sum of the residual and reserve air."

4. *Complementary air* is the volume of air inspired from the position of mid-capacity to that of the maximum possible inflation. It includes the tidal air.

[54] K. R. Harrison, *Failure of the Circulation.* Williams & Wilkins, Baltimore, 1935.
[55] A. Hurtado and C. J. Boller, *J. Clin. Investigation,* **12,** 793 (1933).
[56] R. V. Christie and J. C. Meakins, *J. Clin. Investigation,* **11,** 1099 (1932).

5. *Vital capacity* is the amount of air expired in the fullest possible expiration following the deepest possible inspiration. Vital capacity is the sum of the complementary and reserve volumes.

6. *Total capacity of the lungs* is the sum of the residual air and the vital capacity.

7. *Tidal air* is the amount of air moving in or out during quiet breathing. These relationships are shown more clearly in the diagram in Christie and Meakins[55]—"Lung Volume and Its Subdivision."

In recent publications, pulmonary physiologists have stressed the importance of somewhat more dynamic measurements. Cournand and Richards[50] and Kaltreider and McCann[51] have described ventilatory measurements. These, we believe, should be added to the above terminology:

8. *Minute volume* is the volume of air ventilated per minute under any given conditions. This is the same as the breathing requirement.

9. *Maximum ventilatory volume* is the maximum volume of air that can be ventilated per unit of time (usually expressed in liters per minute). This is synonomous with the *maximum breathing capacity* of Cournand and Richards.[50]

10. *Breathing reserve* is the excess of breathing capacity beyond the actual ventilation in any given state, that is, maximum minute ventilation minus minute ventilation. This may be expressed as percentage of maximum ventilation.

11. *Ventilation equivalent for oxygen* is the amount of air ventilated in order to yield 100 ml. of oxygen to the body.

4. Tests for Ventilatory Efficiency

The ventilatory function is tested by determinations of chest capacity and breathing volume. Probably the most revealing and important measurement is that of maximum ventilatory volume, at least when it is used as a basis for comparison with other measurements. Actually, Peabody[57] has shown that dyspnea is more closely related to vital capacity than to total ventilation.

There are three common methods for the determination of maximum ventilatory volume: (*a*) maximum ventilation in exhausting exercise[51]; (*b*) maximum ventilation with carbon dioxide rebreathing[58]; (*c*) maximum ventilation by performing maximum ventilation effort, using voluntary rate and volume.[50]

The method employed by Kaltreider and McCann appears to give rather uniform results. They measured the air breathed from a spirometer during the last one and one half minutes of exhausting exercise. A test requiring this much co-operation on the part of the patient, no matter how valid its results, is somewhat beyond the scope of what may be employed in general in the examination of industrial patients, whose subjective reactions are extremely variable. Furthermore, the results obtained by this method (average 71 liters per minute for normal male subjects) are somewhat lower than those obtained by the voluntary forced breathing test of Hermannsen[59] as adapted by Cournand and Richards[50] (average 154 liters per minute for males, 100 for females).

The method of carbon dioxide rebreathing is rather difficult to control in the ordinary outpatient clinic and has the added disadvantage of the inaccuracies that develop during rapid breathing in a closed system.

[57] F. W. Peabody, *Harvey Lectures*, **12**, 248 (1916–17).
[58] R. Goiffon, R. Parent, and J. Waltz, *Ann. méd.*, **35**, 362 (1934); **36**, 57 (1934).
[59] J. Hermannsen, *Z. ges. exptl. Med.*, **90**, 130 (1933).

The voluntary rapid- and deep-breathing method described first by Hermannsen[59] and later adapted by Cournand, Richards and Darling[60] and by Wright[60a] also depends on effort by the patient. There is, however, greater likelihood of obtaining reliable results by this method than by those in which maximum exhausting effort is required. The technique has the advantage of being rather simple to perform, and according to the author its results are readily reproducible. In this method maximum deep breathing is measured by having the patient breathe from a spirometer as deeply and as rapidly as possible but with emphasis on depth so that the individual breaths are somewhat short of vital capacity. The patient is tested again for rapid breathing. This time he breathes as rapidly as possible and as deeply but the emphasis is on rapidity. In these tests the author states that a surprisingly uniform pattern is produced. The breathing is carried on for 12 to 15 seconds.

As a substitute for spirometry the exhaled air may be collected in a Douglas bag.[60a] The equipment essential for this technique includes only a close-fitting face mask, a two-way valve of low resistance, a two-way cock, some large rubber tubing, a large Douglas bag, and a flowmeter such as may generally be found in a gas laboratory. The subject inhales room air as deeply and rapidly as possible, but with emphasis on depth, and exhales directly into the Douglas bag for a period of thirty seconds. The volume of air in the bag is then measured. It is desirable to have several men perform this test in a group so that maximum effort can be fostered by competition. Results obtained with this type of maximum effort are ordinarily more consistent than are results obtained by measurement of tidal air, in which psychic factors play a dominant role.

When maximum ventilation is used as a basis for comparison, notation should be made of the method used in determining it so that the results may be compared with those found in the literature.

The functions usually compared with total breathing capacity are vital capacity, minute volume and pulmonary reserve, at a given amount of work or at dyspnea.

Vital Capacity. Peabody[57] in a study of dyspnea in patients with heart disease, and Hurtado and his associates[61, 62] studying patients with pulmonary fibrosis and emphysema, showed that the degree of dyspnea was closely correlated with the vital capacity. Harrison and his co-workers[63] found that the degree of dyspnea in heart disease was more closely related to the expression $\frac{\text{total ventilation}}{\text{vital capacity}}$ than to either of these factors alone, and this has been corroborated by Kaltreider and McCann.[51] Vital capacity can be determined simply by spirometry. Various formulas

[60] A. Cournand, D. W. Richards, Jr., and R. C. Darling, *Am. Rev. Tuberc.*, **40**, 487 (1939).
[60a] G. W. Wright, *personal communication*, 1947.
[61] A. Hurtado, W. W. Fray, N. L. Kaltreider, W. D. W. Brooks, and W. S. McCann, *J. Clin. Investigation*, **13**, 102 (1934).
[62] A. Hurtado, N. L. Kaltreider, and W. W. Fray, W. D. W. Brooks, and Wm. S. McCann, *J. Clin. Investigation*, **14**, 81 (1935).
[63] T. R. Harrison, F. Turley, E. Jones, and J. A. Calhoun, *Arch. Internal Med.*, **12**, 833 (1931).

have also been devised, based on height, weight, body surface area, and x-ray measurements in correlation with certain chest measurements.[64] The closest correlation of predicted values with actual findings was obtained by Hurtado and Fray with the chest measurements and x-ray findings. However, it would appear somewhat simpler and more accurate to use spirometric methods for routine work inasmuch as the equipment is needed for determinations of total ventilation. Kaltreider and McCann found that the vital capacity, the arterial saturation of the blood, and the ability to expand the chest decreased as dyspnea increased. Dyspnea is experienced when the expression $\frac{\text{total ventilation}}{\text{vital capacity}}$ is greater than 51 (with total ventilation determined by exercise method), and when this value is exceeded at low levels of work it is an indication of pathological dyspnea. The maximum ventilation is only roughly proportional to vital capacity in normal subjects, but in patients with pulmonary disease the relation is closer.

Minute Volume. The significance of minute volume is rather striking when it is considered as the breathing requirement of a person at a given time and under given circumstances relative to rest, work, emotional state, and metabolism. This concept of minute volume is ably developed by Cournand and Richards.[50] Minute volume may be measured with a spirometer or by collecting air in a Douglas bag. This measurement is important because from it and the maximum ventilation we obtain the breathing reserve (Maximum Ventilation minus Breathing Requirement). Minute volume may be compared directly with maximum ventilation as a percentage, i.e., (minute ventilation)/(maximum minute ventilation) x 100. In studies by Kaltreider and McCann[51] it was found that dyspnea was first noted by normal individuals at values between 46 and 70 per cent, with an average of 59 per cent. In patients with pulmonary disease the percentage often may exceed this value and at rest may even be well above it.

Pulmonary Reserve. The excess breathing capacity beyond the actual ventilation (minute volume) in any given physical state is the breathing reserve. Cournand and Richards have discussed this concept as follows:

The maximum breathing capacity in each subject is a fixed value and the breathing reserve varies inversely with the breathing requirement. For comparative purposes this may be expressed in per cent of maximum breathing capacity. Thus, in a subject whose maximum breathing capacity is 150 liters per minute, and ventilation at rest is 5 liters per minute, the breathing reserve is $150 - 5 = 145$ liters; and the ratio

$$\frac{\text{breathing reserve}}{\text{maximum breathing capacity}} \times 100 \text{ at rest} = \frac{145}{150} \times 100 = 96.6 \text{ per cent.}$$

Similarly, in the same subject, if the ventilation during exercise is 25 liters per minute, the reserve is $150 - 25 = 125$ liters per minute and the ratio is 83.3 per cent. In 37 patients out of 105 who were given a standard exercise test without

[64] A. Hurtado and W. W. Fray, *J. Clin. Investigation*, **12**, 807 (1933).

experiencing dyspnea, the reserve (even in the first minute following exercise) was 73 per cent of the maximum breathing capacity. Although dyspnea was complained of by a few patients when the reserve was 75 per cent of maximum breathing capacity, the threshold of dyspnea was almost always between 60 and 70 per cent of the maximum breathing capacity. It is of interest if possible to predict, from findings in a patient at rest, whether dyspnea will occur easily. These authors found that if

$$\frac{\text{breathing reserve}}{\text{maximum breathing capacity}} \times 100 \text{ at rest is above } 93$$

no dyspnea will develop with the standard exercise used.

5. *Tests for Respiratory Insufficiency*

The respiratory function is best evaluated by determining the oxygen used from inspired air, the carbon dioxide given off in expired air, or the oxygen content of arterial blood.

Ventilatory Equivalent for Oxygen. The oxygen used is usually determined as the ventilatory equivalent, that is, the number of liters of air breathed in order to supply 100 ml. of oxygen. Such measurements can be made by analyzing samples of expired air for their carbon dioxide and oxygen content by a method such as that described by Van Slyke and Sendroy,[65] or a fairly accurate determination may be made by rebreathing an air–oxygen mixture from a closed system spirometer, removing the carbon dioxide chemically and measuring the oxygen used by the decrease in the spirometer content. There is considerable variation among normals in oxygen consumption, and it is probable that oxygen saturation of arterial blood is the better indication of aeration of blood as it passes through the lungs.

Oxygen Saturation of Arterial Blood. When lung capillary perfusion by oxygen is satisfactory there is usually a high percentage of oxyhemoglobin in the blood and this usually does not fall below 95 per cent even with severe exercise. (See Oxygen, Volume II.) A decrease in oxygen saturation of arterial blood may be due to various causes. In chronic pulmonary disease anoxemia may be caused by the flow of blood through capillaries that are unventilated or poorly ventilated. In heart disease pulmonary congestion may produce inadequate capillary ventilation. Also in heart disease the general circulation may be so retarded that the blood is seriously depleted of oxygen when it reaches the lungs. Determinations of the oxygen and carbon dioxide contents may be performed on the Van Slyke apparatus. This is, of course, somewhat too tedious and time-consuming for routine work in industry. Recently there has been developed a spectrophotometric method[66] for determining the oxyhemoglobin count of blood in the ear lobe. The procedure is simple and is apparently within the same degree of accuracy as chemical methods. It might well be adapted for investigations into blood oxygenation as there is a time lag of only about five seconds and continuous readings may be obtained.

[65] D. D. Van Slyke and J. Sendroy, Jr., *J. Biol. Chem.*, **95**, 509 (1932).
[66] G. A. Millikan, *Rev. Sci. Instruments*, **13**, 434 (1942).

6. *Exercise Tests in General*

Tests depending upon either maximum effort or moderate effort are employed in measuring pulmonary or cardiac efficiency. Maximum effort or effort to fatigue and dyspnea are sometimes used and have their place in the study of pulmonary physiology. For a study of the effects of maximum effort, the most satisfactory equipment for measuring the amount of work performed is the bicycle ergometer. However, for most investigations in industrial clinics moderate exercise may give valuable information as to the state of the patient. In moderate exercise the patient may be asked to squat, hop fifty times, lift a weight repeatedly, etc. None of these tests, however, is weighted to take into consideration normal variations in age and sex. In this respect the Master Two-Step Test[67] has definite advantages as it has been well standardized at least for cardiac function as to age and sex, is simple to perform, and is almost quantitative in terms of foot-pounds of work per given time.

7. *Summary*

An attempt should be made by plant physicians and those charged with the management of workers in industries in which silicosis is a hazard to determine actual disability in patients. By the use of simple respiratory equipment, such as a slightly modified basal metabolism apparatus,[60] the vital capacity and maximum pulmonary ventilation can be determined. The breathing requirement at rest and in standard exercise can be measured with a Douglas Bag or a Tisot Spirometer. Such examination should be possible within a reasonable time even for a busy industrial physician, especially if clerical help is utilized for occupational history taking and nurses are available for the routine portions of the examination. If ventilation is measured by modern methods commonly employed industrially by physicists, as deflection of a wire or alterations in heat conductivity, pneumotachograms[68,68a] can be included in the data without requiring any additional time. In this way considerable information on a new diagnostic procedure for lung and chest diseases (measurement of changes in rate of air flow during the different phases of the respiratory cycle) might be obtained. True, the appraisal of disability by pulmonary function tests is no substitute for appraisal by sound experienced clinical judgment; but it furnishes records for year by year comparison, and it gives definite facts on which to base medical-legal opinion as to disability. In any consideration of disability in pneumoconiosis one fundamental concept must be emphasized. From an economic and sociological point of view it may be wrong to consider a patient as having disability if experience demonstrates that he is capable of doing his daily work. This is especially true if conditions are such that aggravation of an existing condition is unlikely.

[67] A. M. Master and E. T. Oppenheimer, *Am. J. Med. Sci.,* **177,** 223 (1929).

[68] A. Fleisch, "Neuere Ergebnisse uber Mechanik und propriozeptive Steuerung der Atmungsbewegung." *Ergebn. d. Physiol.* **36,** 249 (1934).

[68a] L. Silverman, *J. Ind. Hyg. Toxicol.,* **28,** 183 (1946).

II. CONTROL OF SILICOSIS IN INDUSTRY

1. Engineering Control

The fundamental basis for silicosis prevention is engineering control. Enclosed processes, exhaust ventilation, wet methods, and other engineering techniques can be used to insure safe concentrations of dust in the air breathed by workmen. Engineering control of dusts is discussed in Chapter Ten.

Personal protective equipment such as filter respirators and air-line or supplied-air respirators (See Chapter Fourteen) will under some circumstances afford protection, but such devices are poor substitutes for air sufficiently free of dust to prevent the development of pneumoconioses.

2. Medical Control

All employees with potential exposure to dangersous concentrations of free silica should be given annual medical examinations. These should include x-ray films of good quality competently interpreted, clinical examinations, laboratory examinations in cases where it is necessary to determine infection or concomitant disease such as cardiocirculatory dysfunction, and pulmonary function tests. When there is a question of tuberculous infection, the patient should be examined with sufficient frequency and detail to determine the exact status of the disease.

The type of routine x-ray examination used will be a major factor in determining the cost of the program to the medical department. Most roentgenologists feel that the standard 14-in. × 17-in. film is necessary for definite diagnosis. However, as a screening procedure, several less expensive films are available. Paper film is sometimes substituted for ordinary transparent film. Roentgenograms of this type usually show too little detail to be satisfactory even as a screening process. Roentgenograms of the 35-mm. or 4-in. × 5-in. size, on the other hand, may be used rather successfully for differentiating normal from pathological chests. The 35-mm. film is cheaper and requires less time for developing than the 4-in. × 5-in. It must, however, be used purely as a screening device, as there is not sufficient detail for diagnosis of abnormal findings. Films of the 4-in × 5-in. size frequently may be interpreted directly, necessitating the re-x-raying of fewer employees.

The approximate relative cost of the different sizes of film in the amounts used by large industries is as follows:

Size of film	Cost per patient (approx.)
35-mm. film	4½¢
4-in. × 5-in. film	7 ¢
14-in. × 17-in. film	80 ¢

The number of employees to be examined would alter this but the relative costs should remain fairly constant.

The value of the routine chest survey in the control of silicosis cannot be overstressed, and if photoroentgenograms are used for screening purposes costs may be reduced to a level that can be absorbed by most industries.

The decision as to whether or not a workman should continue at his work is a serious responsibility and requires great care on the part of the examining physician as well as a thorough understanding of working conditions in the particular occupation and an appreciation of public health and moral responsibility both to the individual and to his associates. As a guide for management of the patient with silicosis or tuberculosis, Lanza[69] has formulated the following rules for the various general groups seen:

"I. Partial disability due to silicosis without infection:

"(a) May continue at usual occupation, if environment is satisfactorily controlled as regards dust concentrations and tuberculosis contact;

"(b) Degree of fibrosis and rate of development may require that the individual seek less arduous employment and avoid even minimal exposures to silica-containing atmosphere.

"II. Partial disability due to silicosis with complicating pulmonary infection:

"(a) Primary silicosis. Infection mild and nontuberculous. In most instances, after successful treatment of nontuberculous complicating infection, may be allowed to return to usual work, provided environment under which they are working is safely controlled.

"(b) Primary silicosis with pulmonary tuberculosis as complicating infection. Those individuals with silicosis who develop pulmonary tuberculosis are considered totally unfit for further employment in an industry affording even minimal exposures to free silica. This disability is obviously total so long as active tuberculosis is present. Following successful treatment, these cases regain their health to the point where they can be safely employed at other work."

3. Aluminum Prophylaxis and Therapy

The use of aluminum for the prevention of silicosis was first reported by Denny, Robson, and Irwin[70] in 1937. At about the same time similar investigations were undertaken by Gardner and his associates. Since that time considerable attention has been focused on aluminum and its compounds both in laboratories and in clinics.

Tabershaw and Tebbens[71] summarized the principles that have evolved from laboratory work on both finely divided metallic aluminum and amorphous hydrated alumina as follows: If alumina and silica localize in the same phagocytic cell the effect of the silica is neutralized. Further progression of the tissue reaction characteristically produced by silica is then arrested. Mature silicotic nodules become static, and immature lesions (inflammatory and early fibrous changes) are resolved. Aluminum may remain in the tissue and protect the individual for a long period—over a year. Aluminum does not ordinarily produce toxic effects in the tissues, although it appears to increase the susceptibility of experimental animals to tuberculosis when large doses are given.

Occasionally, allergy to aluminum has been reported,[72] but this is apparently a rare occurrence. Denny, Robson, and Irwin have preferred to use metallic aluminum, but Gardner has found that certain hydrated aluminas are more satisfactory. McIntyre Research Limited, the United States agency created for licensing the use

[69] A. J. Lanza, *Silicosis and Asbestosis.* Oxford Univ. Press, New York, 1938, p. 56.

[70] J. J. Denny, W. D. Robson, and D. A. Irwin, *Can. Med. Assoc. J.*, **37**, 1 (1937); **40**, 213 (1939).

[71] I. R. Tabershaw and B. D. Tebbens, *J. Ind. Med.*, **14**, 709 (1945).

[72] L. H. Cotter, *J. Ind. Hyg. Toxicol.*, **26**, 7 (1944).

of aluminum by physicians for therapeutic or prophylactic purposes, makes only metallic aluminum available. Some investigators, notably Hannon,[73] have reported marked success in the treatment of patients with severe disability. However, when purely objective criteria have been used to measure disability the results have been somewhat less striking. Gardner, Dworski, and Delahant[74] have suggested that variations in response to aluminum therapy may be due in part to the nature of the dust that has caused the silicosis. They suggest that dust which is primarily free silica may react with aluminum more readily than dust which contains high percentages of iron. The use of aluminum generally in industry for the therapy or prophylaxis of silicosis should be contemplated only with the utmost caution.

I. ASBESTOSIS

Asbestos is a hydrated magnesium silicate. More than 90 per cent of the raw mineral used in this country and Great Britian is produced in the Canadian chrysotile mines. Asbestos is used in two general types of manufacturing processes. It may be used either by itself or mixed with other insulating materials such as diatomaceous earth for fireproofing, packing, or insulating; or it may be combined with cotton and woven as a textile for fireproof and heat-resistant clothing and other substances. Lanza[75] estimates that there are about 10,000 persons exposed to asbestos in the United States. Most observers feel that the incidence of asbestosis in American asbestos workers is quite low. Asbestosis has, however, been reported more frequently in England and Canada.

Lanza, McConnell, and Fehnel[76] concluded from their study of asbestosis that: Prolonged exposure to asbestos dust causes pulmonary fibrosis different from that produced in silicosis and demonstrable by roentgenogram. Clinically it appears to be milder than silicosis.

Definite cardiac enlargement frequently was found to be associated with asbestosis.

A predisposition to tuberculosis, due to asbestos dust, was not indicated although it was not known to what extent asbestosis may add to the mortality from pneumonia and acute nontuberculous pulmonary infections.

Symptoms. The onset of asbestosis, as of silicosis, is slow although symptoms are apt to be somewhat more marked than in silicosis. In silicosis there may be marked x-ray findings with little complaint of symptoms, whereas the opposite is likely to be the case in asbestosis. As in silicosis, dyspnea is the cardinal symptom. Anorexia occurs frequently in advanced stages, and cyanosis and clubbing of the fingers are apt to appear with greater constancy in asbestosis.

Pathology. The fibrosis in asbestosis is diffuse and tends to predominate in the basal portions of the lungs in contrast to the generalized nodular fibrosis of silicosis

[73] J. W. G. Hannon, *Trans. Can. Inst. Mining Met.*, **48**, 180 (1944).
[74] L. U. Gardner, M. Dworski, and A. B. Delahant, *J. Ind. Hyg. Toxicol.*, **26**, 211 (1944).
[75] A. J. Lanza, *J. Am. Med. Assoc.*, **106**, 368 (1936).
[76] A. J. Lanza, W. J. McConnell, and J. W. Fehnel, *U.S. Pub. Health Repts.*, **50**, 1 (1935)

with a predominance in the upper portions of the lung. Bronchiectasis and bronchiolectasis are frequent, especially in the more fibrous portions. Whereas the proliferation of fibrous tissue is caused by chemical action in silica exposure, it is induced by mechanical action in asbestos exposures. Gardner[77] found that the fibrosis-producing character of asbestos could be almost eliminated by grinding the fibers so that no particles more than 2 μ in length were present. As previously mentioned, asbestos is classified among the inert dusts.

Microscopic Anatomy. Johnstone[78] described the microscopic appearance of the lungs somewhat as follows: in the early phases of the disease there is thickening of the alveolar septa which results from fibroblastic proliferation. The alveolar spaces contain numerous phagocytes. With progression of the disease fibrosis becomes more marked; the alveolar structure gradually disappears, and in its place there is now dense fibrous tissue. The few alveoli that remain in the area of fibrosis are lined with low cuboidal epithelium giving them an almost glandular appearance.

Scattered throughout the lung in both the diseased and healthy parts are spindle-shaped structures described first by McDonald.[79] These bodies are 20 to 100 μ in length and are bulbous on one or both ends so that they appear club- or dumbbell-shaped. They are brownish in color, do not stain, and give a Prussian-blue reaction for iron. Simson[80] has produced these bodies in guinea pigs by experimental exposure to atmosphere containing asbestos. Lynch[81] concludes that these "curious bodies" signify exposure to asbestos dust but do not necessarily indicate asbestosis.

X-Ray Examination. For an excellent review of roentgenographic findings in both silicosis and asbestosis the reader might well refer to Pendergrass.[82] Characteristic differences in the roentgenographic findings in silicosis and asbestosis are tabulated below:

Asbestosis	Silicosis
Fibrosis diffuse (film may have ground glass appearance from pleural involvement).	Fibrosis nodular.
Findings may be either bilateral or unilateral.	Findings characteristically bilateral.
Lesions largely in the lower one half or two thirds of the lung fields.	Lesions predominately in the upper two-thirds of the lung fields.
Emphysema in upper portion of lung fields.	Emphysema in lower portion of lung fields.

Control. Prevention of asbestosis depends entirely upon preventing exposure to concentrations of dust sufficiently high to produce the characteristic reaction.

[77] L. U. Gardner, *Ind. Med.*, **9**, 45 (1940).
[78] R. T. Johnstone, *Occupational Diseases.* Saunders, Philadelphia, 1942.
[79] S. McDonald, *Brit. Med. J.*, **2**, 1025 (1927).
[80] F. W. Simson, *Brit. Med. J.*, **1**, 885 (1928).
[81] K. M. Lynch, *J. Am. Med. Assoc.*, **109**, 1947 (1936).
[82] E. P. Pendergrass, "Roentgen-Ray Diagnosis in Silicosis and Asbestosis," in A. J. Lanza, *Silicosis and Asbestosis.* Oxford Univ. Press, New York, 1938.

Dreessen, DallaValle, Edwards, Miller, and Sayers[83] have found evidence to indicate that 5,000,000 particles per cubic foot of air is a satisfactory figure for the maximum permissible atmospheric concentration of asbestos to which workers may be exposed. Definite permissible standards, however, have not been established.

VI. Dust Causing Minimal Fibrosis or No Fibrosis

Gardner[77] has pointed out that any known inorganic dust other than free silica and the asbestos silicates may produce nonspecific dust reactions, as described on page 486. X-ray markings may be found in other conditions such as chronic infection and heart disease. No interference with pulmonary function or disability is produced by dust of this type and there is no influence on susceptibility to tuberculosis.

A. SILICATES

McCord,[84] from a number of sources, has compiled a list of the commonly used silicates, which is presented here:

Olivine—a magnesium silicate widely present in all basic rocks. Many varieties of this stone are known.

Calcium silicate—nonexistent in nature, but a common product of industry; may be found at blast furnaces and in production of cement and hydrated limes. Other silicates of calcium are known.

Willemite—a zinc silicate (rare).

Sodium silicate (*meta*)—the well-known water-soluble silicate, commonly called water glass. This is widely used in industry, notably as a filler in soaps. This is the only crystalline silicate of sodium, the others being amorphous glass.

Tremolite—a magnesium-calcium silicate.

Asbestos—tremolite, actinolite, chrysotile, or amianthus, all of which are essentially magnesium silicates.

Jade—another form of magnesium-calcium silicate.

Crocidolite—"blue asbestos." It is a sodium iron silicate.

Talc—a hydrated magnesium silicate with extensive industrial application.

Soapstone—a form of talc.

Agalite—a variety of talc resembling asbestos. It is used in the coating of paper, and as a paper filler.

Meerschaum—also called sepiolite. It is closely akin to talc.

Serpentine—hydrated silicate of magnesium. It is a common building stone.

Sillimanite—aluminum-containing silicate. The source of many stone tools of the stone age

Topaz—a semiprecious stone of silicate origin. Chemically it is an aluminum fluosilicate.

Fuller's earth—a hydrated silica-aluminum compound, associated with ferric oxide.

Kaolin (*kaolinite*)—many related silicates of mixed constituency.

Clays—hydrated aluminum silicates containing iron. Titanium, quartz and mica, are likely to be present in clays.

[83] W. C. Dreessen, J. M. DallaValle, T. I. Edwards, J. W. Miller, and R. R. Sayers, *U.S. Pub. Health Bull.* No. **241** (1938).

[84] C. P. McCord, *Ind. Med.*, **2**, 4 (1933).

Fire clay—refractory clays, low in alkalies, but high in iron and titanium.

Ultramarine—a silicate of aluminum. It is widely used as a pigment, and there are many varieties, including blues, reds, greens, yellows, violet, and white.

Mica—a large group of silicates of different chemical constituency. All are characterized by their well-known tendency for cleavage into thin sheets. It is extensively used in industry, such as in electrical work for insulation.

Garnet—complex silicates of aluminum, iron, calcium, and magnesium. Besides being a semiprecious gem stone, garnets are used as watch bearings, in gem cutting, polishing, etc.

Feldspar—a large group of aluminum silicates entering into many minerals, for example, granite.

Permutite—a sodium-aluminum silicate of complex structure, much used in water softening.

Lava—mixed silicates of volcanic origin.

Pumice—volcanic, glassy, spongy lava. It is primarily used as a polishing agent.

Shale—a loose term applied to clays and other silicates that have been subjected to high pressures in the earth.

Slate—a substance of clay or shale origin, that has been subjected to high pressure and has metamorphosed. It contains or may contain much free silica.

Slags—Products of metal blast furnaces that contain native impurities as well as minerals such as dolomite introduced as fluxes, etc. Almost all forms of silicates may be included. Free silica may be present.

Silicon carbide—carborundum, a synthetic mineral.

Silundum—another form of synthetic silicate, akin to carborundum in chemical structure.

Fibrox—silicon oxycarbide. It closely resembles carborundum and is somewhat similarly made.

It may be stated with some certainty that none of these dusts, unless in combination with free silica, will produce nodular fibrosis; and proof of disability from breathing such dusts is lacking.

B. NONSILICEOUS DUST

Nonsiliceous dusts such as calcite, calcium carbonate, gypsum, limestone, Portland cement, and pyrolusite dusts have been listed in the classification of Miller and Sayers[85] as among those causing an absorptive tissue response and, accordingly, are not considered as producers of pneumoconiosis.

Apparent X-ray Nodulation without Fibrosis. Only brief mention will be made of baritosis and siderosis. Pendergrass[82] reports having seen several patients exposed to barium dust with widespread dense nodulation typical of that seen in simple silicosis. The individuals examined were symptom-free and not incapacitated. Sander[86] has described a similar condition caused by the inhalation of iron oxide fumes at welding operations. Exposure to iron dust or fume may produce an x-ray picture characterized by generalized nodulation. Autopsy specimens have revealed that the nodules are collections of iron with no tissue reaction or fibrosis.

[85] J. W. Miller and R. R. Sayers, *U.S. Pub. Health Repts.*, **56**, 264 (1941).
[86] O. A. Sander, *J. Ind. Hyg. Toxicol.*, **26**, 79 (1944).

VII. Dust Causing Chemical Irritation

It is hardly necessary to enumerate in detail the chemical irritants. These are usually either alkaline or acid in their reaction. Examples of the alkaline group are hydroxides, cement, and soap; and of the acid group, acids, fluorides, and chromates.

Such chemicals may irritate the skin causing erythema or burns, even to the point of necrosis. Injury to the conjunctivae may occur with lacrimation and conjunctivitis; or this type of dust may produce inflammation of the nasal mucosa, sometimes to the extent of ulceration of the nasal septum. These substances also may irritate the remainder of the respiratory tract sufficiently to induce coughing and, in more severe exposures, to cause bronchitis or pneumonitis.

There is little evidence to suggest that prolonged exposure to irritant dust, in concentrations that are too low to produce symptoms at the time of exposure, will cause chronic disease or increase susceptibility to infection. Local irritation by dust may result from purely mechanical as well as chemical characteristics. Mechanical injury may result from breathing long sharp fibers as of lint or other vegetable materials.

A severe and even fatal pneumonitis may follow the inhalation of cadmium dust or fume. This is particularly important since the dust does not produce any immediate irritation or warning symptoms. A few hours following exposure symptoms of gastritis may develop and subsequently pulmonary edema and pneumonitis may occur.

Beryllium has recently been considered as a cause of occupational disease because of the occurrence of acute and chronic manifestations in beryllium workers. The acute phase has been officially named[86a] "Acute pneumonitis of beryllium workers" and the chronic phase has been named[86a] "Pulmonary granulomatosis of beryllium workers."

The acute reactions are characterized by dermatitis, conjunctivitis, irritation of the upper respiratory tract and, in some instances, pulmonary edema. Such lesions may be associated with exposure to the acid compounds of beryllium and may arise in beryllium extraction plants.

The chronic lesions in the lungs are granulomatous. There is associated thickening of the walls of the air spaces and subsequent interference with gaseous exchange, producing dyspnea. Cor Pulmonale may develop. Chronic cases have appeared in persons engaged in the manufacture of fluorescent lamps and in the casting of beryllium alloys in which the percentage of beryllium was relatively high. The subject has been well reviewed in the Saranac Symposium on the Beryllium Problem, Sept. 29, 1947.

VIII. Dust Causing Systemic Poisoning

It is not possible to list here the thousands of minerals, drugs, and chemicals that may exert a harmful effect on the body. One need only recall the great surface

[86a] O. A. Sander, *Summary of Saranac Symposium on the Beryllium Problem*, Industrial Hygiene Foundation, 1948.

area of the lungs to realize that they may act as a gateway to the body for entrance of any material that is suspended in the air. If this suspended material is toxic, pathological reactions may result, providing sufficient dust is inhaled to cause injury.

Dust counts ordinarily are not used to measure the degree of air contamination by poisonous substances. With a toxic dust, air contamination is usually defined in terms of weight per unit volume, such as milligrams per 10 cu. meters or milligrams per cubic meters (10 cu. meters is frequently used as the unit of air because this volume roughly approximates the average lung ventilation during an eight-hour working day). Such measurements correspond more closely to measurements used in pharmacological practice. Large particles of a toxic dust may be of greater importance than are large silica particles since the former may be absorbed, in some instances, from the mucous membranes of the upper respiratory tract.

Perhaps the classical example of a dust or fume causing systemic poisoning is lead (see Chapter Twenty-One, Volume II).

IX. Dust Causing Allergic Manifestations such as Dermatitis, Hay Fever, and Asthma

The layman who has consulted his doctor for allergy tests is well aware of the almost innumerable kinds of dust that may cause hay fever, ranging from pollens to house dust or chicken feathers. Since this is not the place for a discussion of immunology, it is sufficient to say that lacrimation, watery nasal discharge, asthma with its difficult expirations, or dermatitis may develop when a person inhales or contacts a material to which he is sensitive. This allergy is usually the result of a previous sensitizing dose or doses and symptoms do not develop, as a rule, until some time has elapsed following the sensitizing exposure (days or weeks). It is probable that any organic dust may be allergenic. Habeeb[87] has attributed bronchial constriction in silicotic patients to silica allergy. This conclusion is based largely on his own findings of eosinophilia in patients with silicosis, and the *in vitro* evidence of bronchial constriction by colloidal silica.[88] A high incidence of eosinophilia has not, however, been found associated with silicosis by other authors. Gardner[89] has reported attempts to use silica on skin tests but was forced to conclude that any reaction was the result of the primary toxicity of silica rather than of allergy to silica. In the light of these findings, further proof would be necessary to show that symptoms associated with silicosis are allergic manifestations.

X. Dust Causing a Febrile Reaction (Acting in an Unknown Manner, Possibly as an Allergen)

Examples of febrile reactions caused by inhalation of dust or fume are metal-fume fever, which is discussed under metallic poisons (Vol. II), and "cotton fever."

[87] W. J. Habeeb, *Ohio State Med. J.*, **41**, 1101 (Dec. 1945).
[88] G. F. Filley, J. G. Hawley, and G. W. Wright, *J. Ind. Hyg. Toxicol.*, **27**, 37 (1945).
[89] L. U. Gardner, *personal communication.*

Workers exposed to zinc oxide fumes, as in the welding or burning of galvanized iron, are subject to a peculiar reaction, consisting primarily of chills and fever occurring some hours after excessive exposure. Details of this reaction are discussed elsewhere, but there is some evidence to suggest that it may be similar to the foreign protein type of reaction.

A similar reaction is found in cotton mill workers, in whom a condition known as "cotton fever" or "Monday fever" occurs. Employees experience a sudden attack of coughing with breathlessness following exposure to cotton lint, after a week end away from the work environment. This reaction is of fairly short duration, and affected persons usually show no further trouble during the week but may have a recurrence of the same condition on the following Monday. Eventually, though, they suffer continually and may have to give up work. Prausnitz[90] has shown that this condition results from allergy to the protein fraction of cotton dust. The febrile response described may be a different entity from the similar condition reported first by Neal, Schneiter, and Caminita[91] and by Ritter and Nussbaum.[92] They found symptoms similar to a cold, with fever and complaints of sinus trouble, occurring in the first few weeks of work rather than consistently on Mondays. The cause of this malady is described as an endotoxin liberated by the bacterium Aerobacter cloacae which grows in the cotton. A similar condition may occur in hemp handlers and those exposed to bagasse.

XI. Summary

The fundamental principles of anatomy and physiology necessary to an understanding of the pneumoconioses have been discussed. Dust has been considered as a cause of extensive pulmonary fibrosis, minimal or no pulmonary fibrosis, chemical irritation, systemic poisoning, allergic reactions, and febrile responses. An attempt has been made to present pertinent data on these subjects in a way that will help engineers and industrial hygienists to understand the physiological problems involved in dust diseases, and in addition to give sufficient medical data to assist physicians in diagnosis and examination of employees exposed to dust.

[90] C. Prausnitz, *Med. Research Council (Brit.), Special Rep. Series* No. **212,** (1936).
[91] P. A. Neal, R. Schneiter, and B. H. Caminita, *J. Am. Med. Assoc.*, **119**, 1074 (1942).
[92] W. L. Ritter and M. A. Nussbaum, *Ind. Med.*, **13**, 966 (1944).

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